



Research papers

Exploration of the munition dumpsite Kolberger Heide in Kiel Bay, Germany: Example for a standardised hydroacoustic and optic monitoring approach

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ABSTRACT

Post-war marine munition dumpsites do exist and are acknowledged by authorities, but their real extent and their effect onto the environment are mostly unknown. Military historic reconstruction and ocean current data (from in-situ measurements and modelled data) indicate that the German dumpsite in the Baltic Sea 'Kolberger Heide' is an active environment with a huge content of discarded munition material (DMM). Repeated high-resolution multibeam and underwater video surveys prove that Kolberger Heide contains more than 1,000 munition objects in the form of e.g. moored mines, ground mines, torpedoes and aerial bombs. An unsupervised seafloor classification was performed to show that corroded munition objects and proud explosives are in direct contact with the diverse local marine flora and fauna. Also the fact that the dumpsite is in close proximity to the shore in very shallow water (less than 15 m water depth) and displacement and burial of mines can be observed, demand an effective and standardised monitoring procedure. Via the combined approach of hydroacoustic and optical methods, areas can be identified, which should be prioritized when it comes to monitoring.

1. Introduction

Unexploded ordnances (UXO) and discarded military munition (DMM) in seas and oceans are of global concern and a threat that affects national and international waters. Because coastal areas are important for shipping routes, serve as fishing grounds, and are of great importance for construction material extraction and offshore energy production, they are particularly vulnerable with respect to munition. To adequately acknowledge the problem of underwater munition the *Geneva International Centre for Humanitarian Demining* (GICHD) released a best practice guide for survey and clearance of underwater explosive ordnance (GICHD, 2016). It refers to the International Mine Action Standard 09.60 (IMAS) and provides state-of-the-art practices and policies for mine clearance in national waters. However, this only deals with those cases where clearance and remediation is urgently needed due to acute safety risks. Measured by the amount of DMM and UXO in international waters remediation of all munition is rather unrealistic in the near future. The

costs of such a plan are an important factor why marine munition has not been seriously addressed so far. The awareness rose with an increased use of the seafloor as construction ground for oil and gas installations, cables and wind power plants; substantial efforts are thus being made for the detection and clearance of munition in new construction areas as well as shipping routes. Officially designated munition dumpsites are usually not within the focus of surveys because they are prohibited areas and not relevant for marine traffic or constructions.

Beddington and Kinloch (2005) state that all types of munition can be dangerous in case of direct contact since dumped conventional munitions incorporate large amounts of explosives and therefore carry two sorts of risks: the risk of uncontrolled detonation and the risk of releasing toxic explosive-related compounds into the water (Carton and Jaguiewicz, 2009). Trinitrotoluol (TNT), as an essential part of many World War II (WWII) explosives and its degradation products have been identified as cancerogenic and therefore a threat to human health (Yan et al., 2002; Beck et al., 2018, 2019). Studies show that explosives

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accumulate in aquatic invertebrates (e.g. blue mussels, worms) and thus have a high potential to enter the food chain (Belden et al., 2005; Strehse et al., 2017; Appel et al., 2018). The rate of release of toxic explosives, caused by ongoing corrosion is a complex issue. Metal corrosion depends on a variety of factors as described in Wojciech and Fabisiak (2017), Silva and Chock (2016) and Hamilton (2003). Besides that munitions were fabricated from different kinds of material, the time of exposure and local physico-chemical conditions such as the availability of dissolved oxygen, seafloor currents, degree of burial and microbial activity make it very difficult to predict the state of corrosion of munition housings and its further developments.

For Northern Europe, the Helsinki Convention in 1974 introduced first guidelines for the protection of the marine environment of the Baltic Sea area (Carton and Jagusiewicz, 2009). This led to the federation of the bordering states and the European Economic Community, and the ratification of the HELCOM convention ('Baltic Marine Environment Protection Commission - Helsinki Commission') (Carton and Jagusiewicz, 2009). With signing the convention the parties agreed to prohibit sea-dumping of waste, including chemical and conventional munitions (Carton and Jagusiewicz, 2009; HELCOM, 2014). Equivalent the OSPAR ('Oslo-Paris Convention for the Protection of the Marine Environment of the Northeast-Atlantic') convention applies for the North Sea area (OSPAR Commission, 2007). In addition the European initiative of the Marine Strategy Framework Directive (MSFD) aims for establishing a good environmental status of European waters by 2020. Within the directive's descriptor 8, munition disposal sites are explicitly named as a source for contamination and pollution (Law et al., 2010).

To fulfill the MSFD, Germany e.g. has established a monitoring program called BLMP (Bund/Länder Messprogramm). This programme has released a public report about the status of munition contamination within German waters (Böttcher et al., 2011). It is updated yearly, but an effective monitoring procedure has not yet been established. About 300,000 tons of conventional munitions and 5,000 tons of chemical warfare (CW) material have been disposed of into German waters of the Baltic Sea. The North Sea contains around 1,300,000 tons of conventional and 9,000 tons of chemical munition (Böttcher et al., 2011). Besides unexploded ordnance from combat and bombing, all kinds of munition from onshore munition depots have been dumped after WWII in nearshore areas. Instead of shipping the munition to the official dumpsites, it was common practice to start dumping along the way to the designated areas – also known as 'on-route-dumping' (Böttcher et al., 2011, 2015). This and the unintentional dislocations of ordnance by fishery and stone-fishing activities, make it difficult to estimate exact numbers of munition inside those areas (Beddington and Kinloch, 2005; Böttcher et al., 2011, 2015, 2016). Dumpsites are clearly indicated on marine nautical charts and marked by buoys at the sea surface, but despite this, their actual content and extent of munitions just outside the dumpsites is barely known (Beddington and Kinloch, 2005; United Nations Mine Action Service, 2014).

If not blown in place, defused munition is usually not taken out of the water but is transported by the Explosive Ordnance Disposal agencies (EOD) to a marine dumpsite instead (Böttcher et al., 2013, 2014, 2015, 2016, 2017, 2018). This is also done because WWII explosives, having rested underwater for seventy years, become increasingly unstable and the risk of a spontaneous detonation during transport, particularly onshore, has strongly increased (Pfeiffer, 2012). However, this practice is depending on the type of munition. Smaller munition like grenades and cartridges are mainly removed by the EOD and disposed onshore (99.96% removed in Kiel Bay) whereas sea mines, ground mines and torpedo heads are rather relocated after defusion (69.37% relocated in Kiel Bay) (Böttcher et al., 2013, 2014, 2015, 2016, 2017, 2018). Due to this necessary time-consuming and costly practice, the number of munition objects in the sea is effectively not decreasing.

Due to the proximity of munition dumpsites to shore and thus densely populated areas as well as marine shipping routes, it is urgent to gain a better insight of the actual state of the different munitions under

water. As the problem will not disappear but rather spread, it is necessary to establish monitoring procedures for long-term observations and risk assessments of those dumpsites. Here we present results of the German BMBF-funded project UDEMM ('environmental monitoring for the delaboration of munitions in the sea'). For implementing the HELCOM guidelines from 2013 (HELCOM, 2013) and the Marine Strategy Framework Directive, a workflow was developed within the project presenting a current state-of-the-art approach for monitoring conventional munition dumpsites, including chemical, biological and toxicological investigations. As part of the UDEMM project, this study gives an inventory in terms of munition distribution of the official conventional munition dumpsite Kolberger Heide. The work done between 2016 and 2019 acts as baseline study of a research site for following investigations and is part of a conceptual site model (CSM). The importance of CSM has been described within the NATO project MODUM in order to monitor marine chemical dumpsites inside the Baltic Sea (Beldowski et al., 2018). The research area Kolberger Heide was chosen to establish and test hydroacoustic and optic monitoring approaches for shallow water munition dumpsites (less than 25 m water depth). Even though the presence of munition in this area was already known from German Navy data (Kretschmer and Jans, 2016; Kunde et al., 2018), the actual number and preservation status of DMM was unclear. The multilayer approach also enabled to investigate potential location and burial changes of munition objects over time that might give indications for future changes and developments.

Due to extensive work in international and national archives, the historic-military past of the study site Kolberger Heide could be well reconstructed. Physical oceanographic conditions have been determined through oceanographic modelling and in-situ measurements using ADCPs and CTDs; respective data will be shown. However, the main focus has been hydroacoustic surveys with high-resolution multibeam echosounder (MBES) in combination with ground truthing from optical observations and sediment sampling for the identification of munition objects and for developing a seafloor classification map of the Kolberger Heide area at the same time.

We show that a historic analysis of archive material of the area is an important pre-requisite for setting up an adequate monitoring strategy (Carton and Jagusiewicz, 2009; HELCOM, 2013). Such archive analyses provide essential information about the type, number and general location of the munitions guiding the selection of the mapping and monitoring methods. In addition, sediment properties and sediment transport have a strong impact on the depositional setting of the ordnances. Wave- or wind-induced bottom currents can cause scour formation around objects, which can lead to displacement and burial of mines (Menzel and Leder, 2013; Menzel et al., 2018). As these processes also depend on the local sediment properties, sediment sampling must be part of any mapping and monitoring to highlight, where munition burial is likely to have already happen, or might happen in future. Furthermore, good knowledge about local physical conditions is essential to put the deposition and burial of munition as well as the distribution of particulate and dissolved contaminants into perspective of the environment. Focusing on particular areas can significantly reduce the time and costs for monitoring; Strehse et al. (2017) and Beck et al. (2019) show that explosive-type compound concentrations (in water or biota) are strongly coupled to local explosive's exposures. The amount of exposure can change through relocation due to sedimentary processes or corrosion as described in e.g., Menzel et al. (2018) and Wojciech and Fabisiak (2017). Buried munitions might bias monitoring results, risk assessments and remediation strategies planning and in this respect the here presented methods allow identification of sub areas, which should be recommended for further monitoring or in which additional detection methods are required. Beldowski et al. (2018) emphasize five questions, which should be covered during monitoring, addressing environmental contamination, uptake by biota as well as release and spreading of chemical substances. We combined these five questions in three topics that are relevant for defining best suited areas for monitoring in

conventional munition dumpsites in shallow water:

1. Release of toxic compounds and subsequent environmental contamination
 - > identified through open explosives in contact to flora and fauna
2. Relocation of DMM into sensitive regions (marine traffic routes, nature reserves, beaches, construction sites, etc.)
 - > identified through migration/displacement, temporary burial or scours around object
3. Unsuitable/incomplete mapping methods for complete DMM identification
 - > indicated by scours around objects that point towards potential burial; change of sediment composition/properties.

Monitoring enables the predictions of e.g. contamination rates, spreading and accumulation of toxic substances and thus monitoring results are an essential input for any risk assessment and decision-making processes for remediation planning of munition dumpsites (Landquist et al., 2013; Landquist, 2016).

1.1. Study area description

Kolberger Heide is one of eight official munition dumpsites in German waters of the Baltic Sea (Fig. 1; location BKB04L, Böttcher et al., 2011/appendix 10.2). It is located within the eastern part of Kiel Bay, approximately 2 km offshore and listed as foul ground with explosives in

official nautical charts. Kolberger Heide encloses a munition-suspected-area of approximately 15 km². Within this area, two official dumping grounds of 0.5 and 1 km² size are located and marked with navigation buoys as particularly restricted areas. The water depth of the entire area ranges from 5 to 20 m. Entering the dump grounds is only permitted with a special authorization that has been issued by the competent authorities. Anchoring within these sites is strictly prohibited. Due to the sensitivity of the data in general and the exact location of munition specifically, no coordinates will be displayed or published within this paper.

1.1.1. Military-historic background of Kolberger Heide

The military-historic analysis is based on original historic documents, which were written by the German and British military forces. Bombardments, mine laying activities, records of detonations and mine clearances are very well documented. Nevertheless, the documents need to be carefully analysed within the historic context to ensure correct interpretations. The here presented results are temporary, as numbers can still change with ongoing archive investigation work.

Documents of the provincial and federal archives in Schleswig and Freiburg (Germany) and the National Archive in Kew (UK) provide detailed information about the usage of the area in the past. With regards to war activities, the Kolberger Heide was firstly mentioned in the sea battle on 1st July 1644 during the Swedish-Danish war (1643–1645 CE). After that the area was only used for commercial fishing before WWII, as it was too shallow for the German fleet to enter.

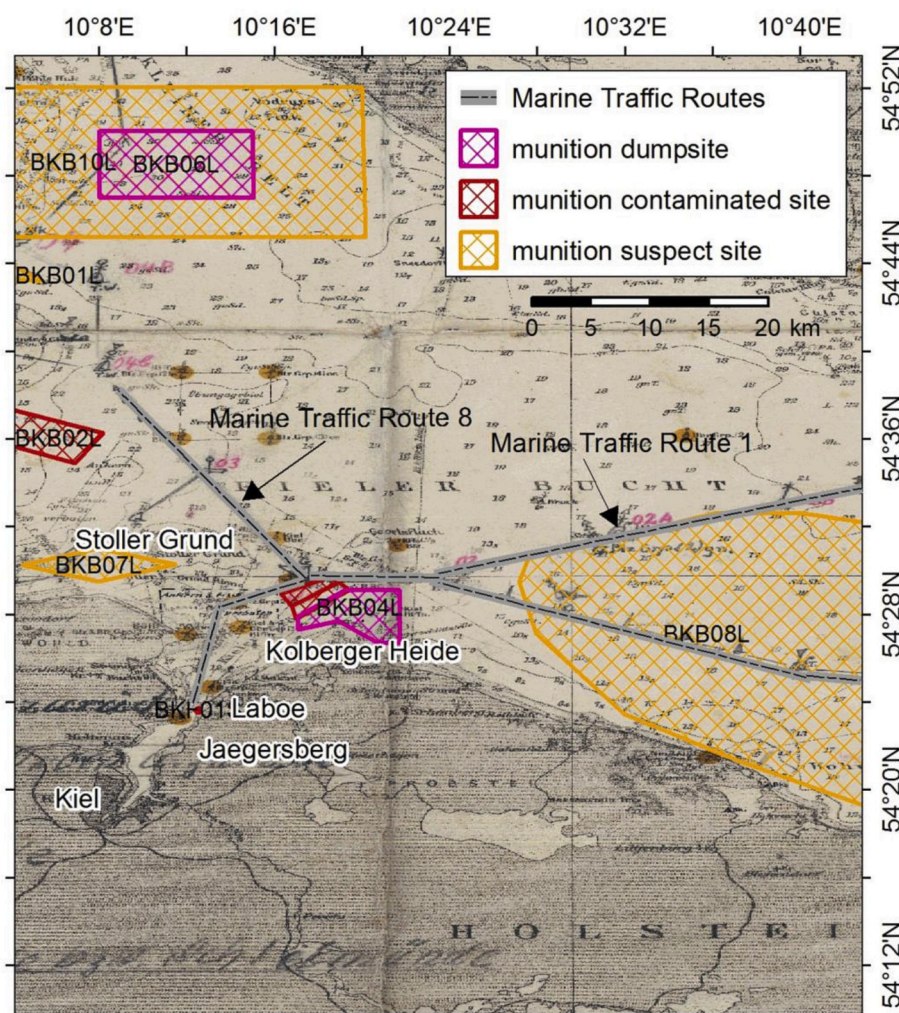


Fig. 1. Section of a nautical chart of the western Baltic Sea, showing Kiel Bight and its actual munition dumpsites (pink); munition contaminated sites (red) and munition suspect sites (orange)). The munition contaminated site BKB08L acts as a recent military training facility, also called 'firing range Todendorf'. The underlying map is originally from 1923 and was used in the WWII for navigation purposes. Grey lines mark the locations of 'safe Marine Traffic Routes' in 1945 (arrows). The German Kriegsmarine tried to keep these navigation routes mine-free during the war. Last hand-written changes on the map were made in 1945. The yellow dots indicate positions of navigation marks and light ships (documents of the Library of Mürwik Naval School; Munition Cadaster "AmuCad", EGEOS GmbH). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

It is possible that before WWII, 28 cm training grenades (steel housing without explosives) were introduced to the area during training exercises of the gun battery in Laboe ([documents of the British National Archives in Kew, Great Britain](#); [documents of the German National Archive/Military Archive \(BaMa\) File RM 43/22, map sections “Befestigungen Kieler Bucht”](#) and [Prange \(1996\)](#)). Apart from that, there are no records of additional munitions entering the area.

The first records from the WWII period report the introduction of munitions in 1940 when the British Airforce started bombing Kiel. Failed bombings, emergency overboard disposal, and targeted attacks on vessels and watch units occurred along the Marine Traffic Route 1 (Fig. 1). This traffic route extended from Kiel to the eastern parts of the Baltic Sea and was constantly surveyed and cleared by the German Kriegsmarine using mine clearing vessels and airborne mine clearing systems. It was the only ‘safe’ path vessels could use during times of war and was therefore an important target for the British Airforce. Because of this, the route was protected by German forces with onshore and vessel-based 12.8 cm anti-aircraft guns. A number of these shells ended up as unexploded ordnance (UXO) in Kiel Bay and also the Kolberger Heide area. To hinder vessel traffic, the British mined the marine traffic route 1, with as many as 3896 British mines also targeting the Kolberger Heide ([Naval Staff History, British Mining Operations, 1939–1945](#)). Because of the high number of mines and resulting losses, commercial fishing was prohibited in Kolberger Heide in 1942 ([documents of the Federal Military Archive “Kriegstagebuch Sperrkommandant westliche Ostsee”](#)). Bombing and mining activities continued until the end of the war in May 1945.

After the war, enormous quantities of captured arms and munitions were dumped into the sea, this was seen as the fastest and at that time safest method to secure and get rid of the weapons. The dumpsites in German waters (North Sea and Baltic Sea) were chosen and approved at 29 July 1945, with Kolberger Heide mentioned as the first dumpsite ([documents of the British National Archives in Kew, Great Britain](#)). Continuous sea-dumping of munitions occurred at Kolberger Heide after that day. This included torpedo heads and mines from the torpedo arsenals in Schleswig-Holstein. Documents from the federal state of Schleswig-Holstein describe dumping of about 24.000 t of all kind of munitions in Kolberger Heide, adding torpedo heads and mines about 30.000 t of munition material is currently assumed to be present at the site ([documents of the EOD from the Federal archive of Schleswig-Holstein](#)). This includes different munition types ranging from gun and pistol cartridges, artillery projectiles consisting of grenades and propulsion cartridges, as well as anti-aircraft ammunition of 2 cm up to 40.6 cm calibre. In addition, the Kolberger Heide site most likely contains explosive charges as anti-tank and anti-personnel mines, rifle grenades or bursting and hollow charges. Bombs ranging from 1 kg up to 500 and even 1,000 kg in size, rockets with diameters of up to 32 cm, as well as marine munitions such as moored and ground mines, torpedo heads, whole torpedoes, and depth charges are present. Some torpedoes that were formerly dumped in the area of Jaegersberger Bridge were re-scuttled to Kolberger Heide and re-dumped. Also, a barge loaded with 500 tons of chemical munition (grenades of 10.5 and 15 cm caliber) and first scuttled in the Little Belt was recovered and re-sunk in the area of Kolberger Heide. In year 1959, boxes with propellant charge powder stored on the upper deck of the barge were salvaged until the chemical munition was discovered. Chemical grenades were partially removed, and the remainder brought together with the barge to Geltinger Bight, where everything was encased in concrete and finally sunk in the North Atlantic ([documents of the EOD of the Federal Archive of Schleswig-Holstein](#)).

As often when dealing with World War I (WWI) and WWII dumped munition, the exact number and type of munition and manufacturer is unknown and therefore all common explosives and propellant charge powders used in WWII have to be assumed to be present at Kolberger Heide. This includes all sorts of filling powder, amatol, ammonite, ammonal, grenade filling 88 and marine explosives such as gun cotton

(e.g., Schiesswolle 36 and 39) as well as special and testing explosives. As long as the absence of these explosives is not proven, they need to be taken into account when a risk assessment for this area is done. After WWII, the Allies intended to only dump defused munition; however it cannot be taken for granted that this was true for all dumped ammunition. Accidents including personal injuries and death happened during the dump work, and thus it needs to be assumed that at least some of the handled munition was still armed. This is especially true for long-period delay detonators, mines with lead fuses or pendulum impact ignition.

The Allies chose further similar regions as Kolberger Heide as munition dumpsites in the Baltic Sea; these include areas offshore Schönhagen and Falshöft in the Lübeck-/Neustadt Bay. It is also known that light-weight munitions like grenades were thrown overboard in Friedrichsort, Stollergrund, Strande Bay, and on route to these dumpsites. These actions are indicated by findings of fishermen and the EOD (BLMP report 2011 and [documents of the Federal Archive Schleswig-Holstein](#)) and highlight the wide spread disposal of munitions in the southwestern Baltic Sea that is German territory now.

Following WWII, Kolberger Heide was not used as a military training area anymore. Nonetheless, munition that was subsequently found along marine traffic routes in Kiel Bay has been defused and relocated to Kolberger Heide by the EOD; this practise is still ongoing ([Böttcher et al., 2013, 2014, 2015, 2016, 2017, 2018, 2019](#)). Historic investigations result in 6,295 mines that were dumped in Kolberger Heide (Fig. 2). However this number neglects small munition like grenades and artillery shells and blocks of explosives without shells. A total weight of 1,637.74 t of explosives is assumed to be still existing inside Kolberger Heide. The diagram in Fig. 2 visualizes that not only the number, but also the weight ratio of shell to explosive is essential when it comes to assess the contamination. Small ground mines do have the largest share on the explosive content in Kolberger Heide.

1.1.2. Regional setting

The geological/sedimentological setting of the area is dominated by glacial processes. Kiel Bay is built up by Pleistocene deposits such as glacial till overlain by meltwater deposits ([Schwarzer and Themann, 2003](#)). The shore area Probstei, south of the Kolberger Heide dumpsite, is a shallow northward dipping Weichselian glacial basal moraine plate

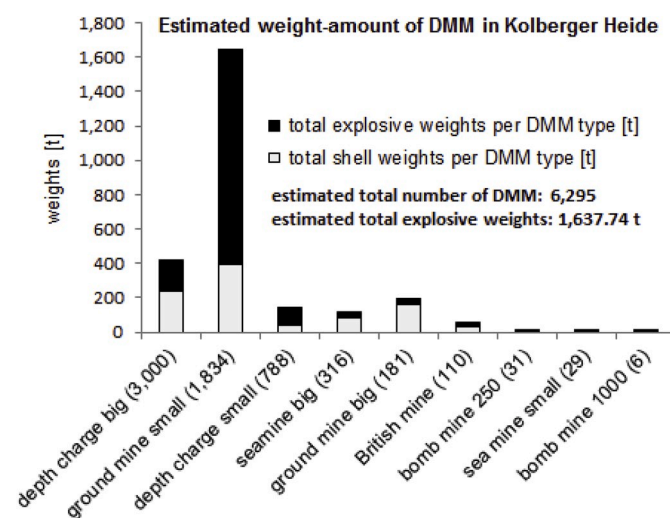


Fig. 2. The diagram shows the estimated total weight-amounts (Y-axis) of DMM in Kolberger Heide for each type of munition (X-axis). Estimates are based on findings in historic records ([documents of the German National/Military Archive BaMa folder RM/1486, “Übersicht Defensiv Minensperren”](#) 1. SKL; [Naval Staff History, “British Mining Operations, 1939–1945”](#); [British Underwater Ordnance, Mine Disposal Handbook, Allied Forces, 1945](#); [OP 1666 German Explosive Ordnance, 1946](#), Allied Forces). The number in brackets behind the munition type gives the number of objects. Weight is given in tons.

(Bressau and Schmidt, 1979). This abrasion platform functions as sediment delivery area for the coastal beaches (Brand, 1955). Typical sediments are clay, sands, gravel and rocks. The sediment transport direction close to the coast is observed to go from west to east. Westerly winds occur stronger and more often in this area, but due to their small fetch area over the water, the wave heights and wave energy generated from the westerly winds are lower than for north-easterly winds (Schwarzer, 1994).

Data from a larger number of hydrographic surveys were used to create a bathymetric map of Kolberger Heide (Fig. 3). The main dumping ground is located in the south of the area in 5–14 m water depth on a shallow platform, which develops towards the north into a more horizontal plain in 19–20 m water depth. The southern part is incised by a shallow trough with a maximum water depth of 14 m. Patches of algae, covering the seafloor with varying density could be observed in underwater video footage and show seasonal variability in their spatial distribution. Small scale ripples of 5 cm height and 20 cm width indicate sediment transport on the seafloor. Their crests are generally N–S oriented and thus perpendicular to the bottom current direction (Fig. 3). Beunaiche (2017) showed that these optically visual ripple structures strongly influence the multibeam backscatter signal, similarly to the observations made by Le Chenadec (2004) and Lurton et al. (2017). Beunaiche (2017) showed that these ripples are not necessarily long-term phenomena as they can vanish completely within two months due to storm events; they most likely reform as soon as the predominant eastward currents re-establish.

In 19 m water depth in the outer area of the dumpsite, otter trawling marks are visibly incised into the soft sediments indicating significant fishing activities (Appendix, Fig. 17). This fishing method uses two doors that are dragged on the seafloor to keep the trawling net open. These doors not only produce characteristic long lasting furrows about 20 cm deep, but also cause disturbances and resettling of sediment and more importantly relocate larger objects on the seafloor (Lokkeborg, 2005). Since 2004 the trawling is prohibited in the Baltic Sea for areas

shallower than 20 m water depth or within 3 miles to the coastline. Despite this, 10–100 h of otter board trawling were noted within this area in 2006 (Sell et al., 2011). Even though Kolberger Heide is not one of the main fishing grounds in Kiel Bay, bottom trawling seems to occur close to the official dumpsite and thus most likely leads to object displacement.

1.1.3. Oceanographic setting

The water body at Kolberger Heide is generally influenced by the exchange processes between the Baltic Sea and the North Sea, with waters flowing back and forth through the Danish Straits (the Little Belt, Great Belt and the Sound). There is a net input of fresh water into the Baltic Sea of approximately 476 km³ per year from rivers and precipitation minus evaporation (Reissmann et al., 2009). Due to its low density this freshwater flows out into the North Sea at the sea surface. Within the deeper basins a permanent sharp vertical gradient in salinity (halocline) at around 60 m depth separates the fresh surface layer from more saline and denser bottom waters. This dense, saline water originates from the North Sea and sporadically but then abundantly, flows into the Baltic Sea during so-called inflow events (for details see e.g. Reissmann et al., 2009). In the shallow waters close to the Danish Straits there is a permanent exchange of water between the Baltic and North Sea (see e.g., Knudsen, 1900; Burchard et al., 2018) which influences the physical dynamics of the Kolberger Heide.

For reconstructing a 10-year record of water currents, temperature and salinity model data of the General Estuarine Transport Model (GETM, Burchard and Bolding, 2002) of the western Baltic Sea set-up was used and fed with data from January 2006 until end of October 2016. Eggert et al. (in prep.) describe this model set-up, including its validation in detail (see also Gräwe et al., 2015; Klingbeil et al., 2014). The high-resolution model was run for the western Baltic Sea using hindcast weather and river run-off forcing data from the German Weather Service (DWD). Daily data were generated with a horizontal grid spacing of 1/3 nautical mile (approx. 600 × 600 m) and 50 adaptive

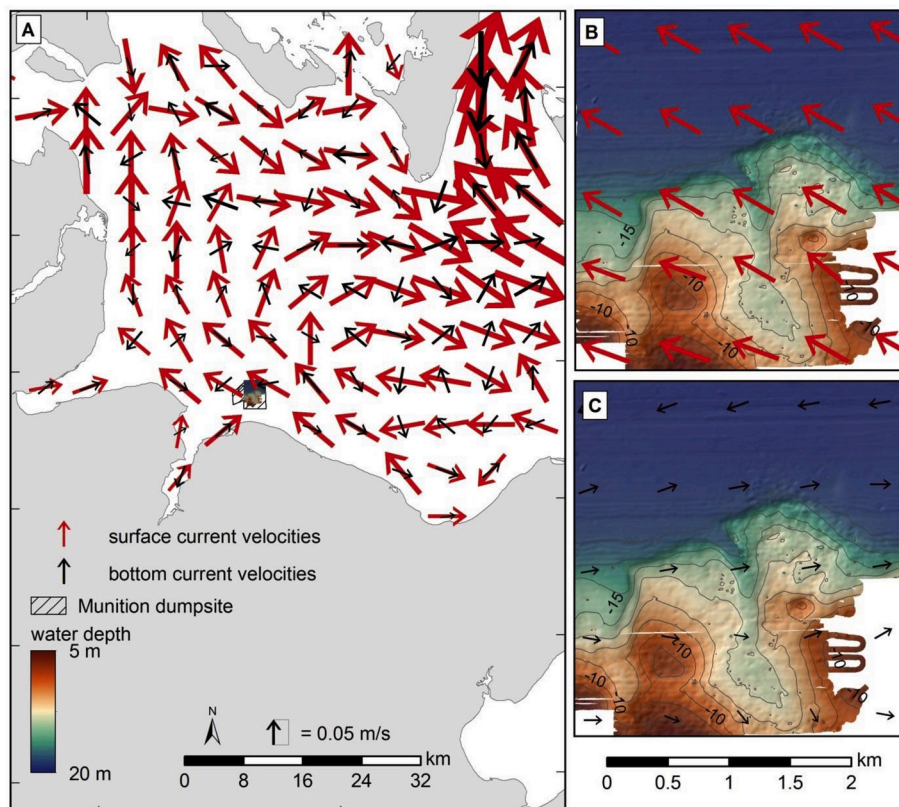


Fig. 3. A: Overview map of the western Baltic Sea and Kiel Bay including the area of the munition dumpsite Kolberger Heide. The arrows indicate the modelled current velocities and directions (red arrows: surface currents, black arrows: bottom currents). B: MBES bathymetric map of Kolberger Heide acquired during surveys from 2015 to 2017 showing water depths ranging from 5 m to 19 m with 1 m contour lines and surface currents. C: Same as B but with bottom currents. Velocity arrow sizes according to legend in A. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

vertical layers (see Hofmeister et al., 2010) with thicknesses varying between about 50 cm and 12 cm.

From this model the bottom-most and surface-most layer were taken and for each grid point the current direction was determined for each time step (3,957 days in total). These current directions were pooled into 36 'angle bins' of 10° bin size and the most populated angle bin was considered as the main direction (current direction shown as arrows in Fig. 3). All current speeds for this most common direction were averaged over the 10-year record for the mean current speed at each grid point.

Despite the often not existing vertical density structure, current strength and direction do show different tendencies between the bottom and surface waters (Fig. 3). At the surface the water flows north-westwards towards the Little Belt whilst bottom currents are directed into the Baltic Sea, consistent with the overall estuarine circulation between the North and Baltic Seas described above. That the surface currents are stronger can be expected as currents in the Kiel Bay are typically wind induced at the sea surface and are slowed down by friction towards the sea bed. Mean surface current speeds within the Kolberger Heide dumpsite are averaged to 0.149 m/s with a standard deviation of 0.021 m/s and range from 0.107 m/s to 0.183 m/s. The main current direction at the sea surface is towards the northwest at nearly all grid points. Near the seabed the currents were substantially (6-fold) slower with an average mean speed of 0.024 ± 0.005 m/s, a minimum of 0.015 m/s and a maximum of 0.035 m/s. Within all but the northern-most part of the dumpsite currents are mainly directed towards the east. This higher variability shows that near-bed currents are more influenced by the bathymetry following the depth contours. Due to its shallow depth of approx. 12 m there is no permanent or even stable seasonal stratification in the Kolberger Heide. Stratification does exist occasionally when saline waters flow into the Baltic Sea along the sea bed or when summer sunshine heats the surface waters. Periods of

stronger winds can destroy this tenuous stratification so that the water column is vertically well-mixed every few weeks (respective data not shown).

For one grid point within the restricted area, the bottom velocity data was used to construct "wind roses" for the four seasons; March/April/May for spring, June/July/August for summer, September/October/November for autumn and December/January/February for winter (Fig. 4).

At the bottom, current speeds are significantly lower (Fig. 3), but also less rectilinear (Fig. 4) compared to the surface (see Appendix, Fig. 19). A clear preferred direction is visible, but the main direction-angle bin only makes 8% of the overall distribution. In all seasons the dominant direction is towards the southeast, although relatively strong currents occurred flowing towards the west. Bottom currents show a stronger seasonal signal in current strength than surface waters. In summer current velocities are lowest (0.0095 ± 0.0099 m/s) and highest in winter (0.0247 ± 0.0214 m/s).

2. Material and methods

2.1. Hydroacoustic mapping

Mine counter measurement surveys (MCM) are generally conducted by national Navies, EOD or commercial field companies. They usually work with technologies including towed side-scan sonar, sub bottom profilers, multibeam echosounder systems (MBES) and marine magnetometers (Flax, 2015; GICHD, 2016). By applying these technologies, areas are mapped and potential munition objects are typically identified interactively by experts. For clearance purposes, each suspicious object needs to be visually inspected by divers or underwater camera systems (by lowered cameras or through remotely operated vehicle operations).

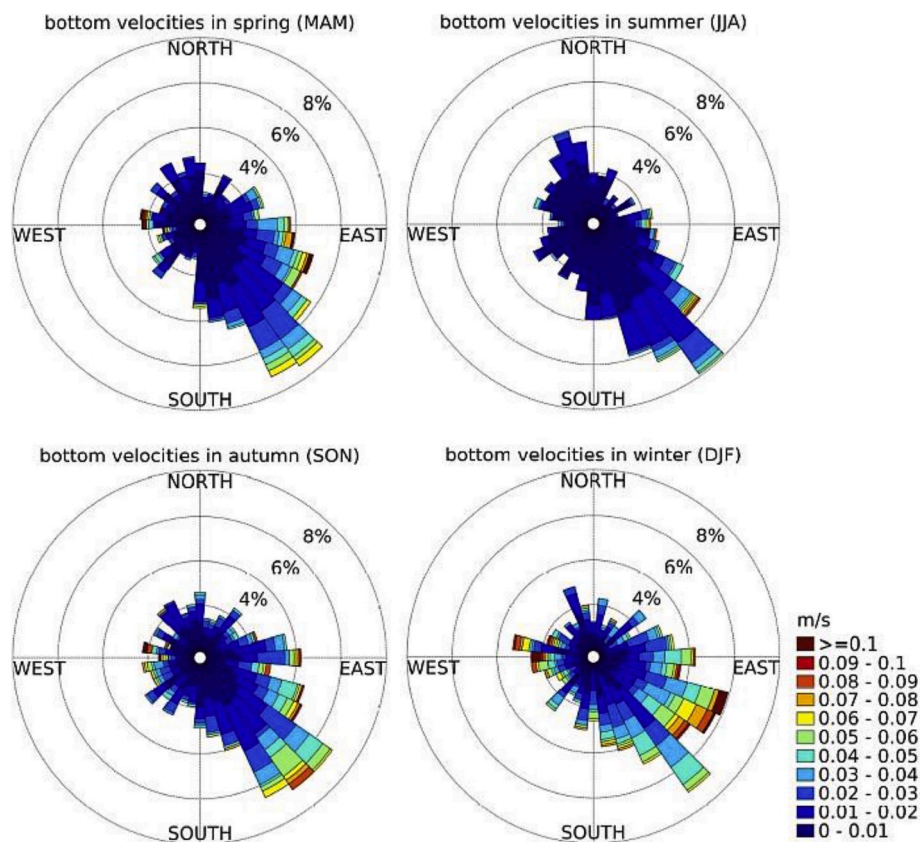


Fig. 4. Rose diagrams of modelled bottom current velocities for four different seasons (spring, summer, autumn, winter). The velocity roses show the current directions grouped into 36 angle bins, with each bin thus representing a 10° span of the compass. From the middle of the circle the angle bins point into the direction in which the current is flowing and their length represents the relative occurrence of current directions within that angle bin.

As this is a time-consuming task, new technologies for mine detection are being developed. Within the SERDP ('Defence Strategic Environmental Research and Development Program') projects MR-1666 and MR-2230, a database containing Synthetic Aperture Sonar (SAS) target signals was initiated. Based on characteristic acoustic target responses the data in the database are used to test different automated target recognition algorithms for discriminating different materials of buried and proud objects. Unfortunately, the signatures are highly dependent on the surrounding environment and thus for establishing a database able to detect and identify 'all' munition, a large set of training samples, covering all types of munition, is required (Kargl et al., 2010; Kargl et al., 2012; Lim, 2015). Within a study from Missiaen and Feller (2008), very-high-resolution seismic and magnetic data were successfully used to investigate buried chemical munition dumpsites in deep waters of the Baltic Sea (e.g., Bornholm Basin; down to 95 m water depth). Depending on the sedimentary conditions, the parametric wave of the echosounder with a main frequency of 10 kHz could penetrate down to a few tens of meters. With a vertical resolution of 10–15 cm, it was possible to detect even small objects of 1–2 m size. Unfortunately, gas-rich sediments can mask objects completely, making detection with seismic devices impossible. In case detection is possible, the correct burial depth can support correcting the mass calculation of magnetic data as the magnetic signal strength varies with object size and burial depth (Missiaen and Feller, 2008; SERDP, 2018). Magnetic data can be used to verify objects detected through acoustic methods to be actually ferrous. As magnetic systems are typically towed behind the survey vessel or used on autonomous underwater vehicles, position errors must be considered.

Multibeam echosounder systems have become state-of-the-art tools in many sea and ocean going surveys. Here, we test their potential as effective tools for monitoring munition dumpsites. Using RTK- ('real time kinematic') GPS navigation during the ship-based surveys, the position accuracy increases to ± 0.03 m; this prevents double detection of objects, as may happen with towed systems. Modern MBESs record snippet backscatter intensities of the received signal for each beam of each ping (Lamarche et al., 2011; Lurton et al., 2015; Lamarche and Lurton, 2018). Such information has been shown useful for mine detection due to the significantly stronger backscatter signal from these hard artificial objects (Kunde et al., 2018). The here shown MBES data were acquired with a RESON T50-P multibeam with specifics as given in Table 1. The cell size of the final data products was chosen to be 0.25 m. With RTK the horizontal and vertical position accuracy is increased to at least 0.03 m. This precision is needed to monitor also minor rearrangements of munition and sedimentary processes as scour formation and burial. Water currents- and wave-induced sediment transport can cause munition, displacement, migration and burial, whereby migration refers to movements of mines for a longer distance. Displacement rather describes the rolling of an object into a scour depression and subsequent burial (vertical displacement). One target area has been surveyed repeatedly in 2018, in order to detect possible relocation of objects (chapter 3.4 Munition migration and its link to seafloor properties, Fig. 14). As these processes are dependent on bottom currents, waves and sediments, knowing the seafloor properties is essential in order to evaluate a munition dumpsite in terms of its stability.

Bathymetric derivatives such as slope, curvature, rugosity or height relative to the surrounding (Topographic Positioning Index TPI) provide an objective terrain classification as base for a more detailed seafloor

classification mapping of habitats. Unsupervised classification was applied to find correlations of these morphological properties, seafloor backscatter signals and ground truth data such as optical observations or data from direct sampling (Brown and Blondel, 2009; Law et al., 2010; Le Bas et al., 2009; McGonigle et al., 2009; Lucieer and Lamarche, 2011; Alevizos et al., 2015, 2018; Lamarche and Lurton, 2017). In this study we show the usefulness of MBES surveys for detailed seafloor classification and highlight the possibility to detect munition objects within the same data set and classification step. For this purpose, several MBES surveys carried out in 2016 and 2017 using different ship-based state-of-the-art high frequency systems (Norbit iWBMS; RESON T50-P) were utilized. For a full seafloor description three spatial scale levels are considered (Table 2), which follow the nomenclature from Greene et al. (2007). Whereby, only the meso-, macro- and microhabitat are relevant for describing Kolberger Heide. The high-resolution bathymetry makes it possible to describe and classify microhabitats which can be directly linked to the visual observations (Table 4) of the same scale.

The IHO special order [*areas where under-keel clearance is critical*] demands that features of a minimum size of 1 m² within a 'full sea floor search' can be detected (IHO, 2008). The ability to detect objects depends on the spatial resolution of the sonar and the sounding density over a certain target; it is thus controlled by the beam footprint on the seafloor (which depends on the beam opening angle, the water depth and pulse length), the ping rate and vessel speed (Hare, 2001). Hare (2001) performed a detailed evaluation of sonars in comparison to IHO specification and showed that survey parameters, such as beam opening angle, refraction deviation and draft can hardly be influenced by the surveyor during data acquisition but need to be considered when data accuracy is evaluated and given. To allow later evaluation of data quality it is essential to provide metadata, such as offsets, patch test results, sound velocity profiles and RTK information and store these with the raw data and data products.

During the surveys of this study, swath angles of 120–130° were used. Due to the partially very shallow water and varying morphology (5–20 m) the line spacing needed to be planned thoroughly to achieve overlapping data and cover as much area as possible within the available survey time. Swath widths varied from 10 to 90 m. As the used ship did not have dynamic positioning the narrow swath made it sometimes impossible to get full coverage, data gaps occur between some profile lines. At least two sound velocity profiles were taken per day to correct the multibeam data for refraction miscalculations.

Data acquisition occurred with the QPS QINSy software; data were processed with QPS Qimera. For most surveys, the backscatter signal was recorded in addition to the multibeam data. To correct the backscatter amplitudes for angular dependencies and for creating a mosaic grid, we used QPS FMGT and snippets backscatter mosaics and bathymetric raster data were exported as ASCII grid files. Terrain derivatives have been calculated using the open source software SAGA GIS (Conrad et al., 2015). To highlight local minima and maxima, the TPI was calculated, comparing the average depth of an inner circular area (*irad*) with the average height of a doughnut shape area with an inner radius of *irad* and a larger outer radius (*orad*) (Eq. (1)). Depending on the object size that should be highlighted the TPI radii need to be chosen carefully (Weiss, 2000).

$$\text{TPI} = \text{depth}_{\text{mean}}(\text{irad}) - \text{depth}_{\text{mean}}(\text{irad-orad}); \text{tpi} > 0: \text{elevation}; \\ \text{tpi} < 0: \text{valley} \quad (1)$$

For our purposes and a grid cell size of 0.25 m, we used *irad* = 1 and

Table 1
Multibeam main settings during surveys.

Frequency	400 kHz
Across-track beam width	0.5°
Along-track beam width	1.0°
Swath width	120°
Ping rate	21 p/s
Pulse length:	31 μ s
Beam number	512

Table 2
Observed morphological scales and their dimensions after Greene et al. (2007).

Scale	Dimensions	Description
Mesohabitat	tens of m to a km	mounts, canyons, valleys, plateaus
Macrohabitat	m to tens of m	bedforms, craters, rock/mine piles
Microhabitat	few tens of cm to a few m	rocks, mines, other objects

$orad = 4$. Three other derivatives are calculated directly from the bathymetry. The slope was calculated via the slope algorithm from Zevenbergen and Thorne (1987) implemented in SAGA GIS. It analyses a 3x3 submatrix around each cell. The real surface area considers the slope in each grid cell for deriving the respective value (Grohmann et al., 2009). The general curvature as final derivative is again based on a 3x3 matrix (Zevenbergen and Thorne, 1987). Because results of bathymetric derivative calculations are significantly dependent on the initial cell size, the input grid cell size was chosen as small as possible, here 25 cm. Previous studies successfully used either the shape (Mayer et al., 2007) or the backscatter snippets (Kunde et al., 2018) for munition detection via multibeam. Because the Kolberger Heide dumpsite is partly composed of former glacial sediments with a number of rocks and boulders that can be easily mistaken as munition and vice versa, a multi-proxy approach is required, consisting of bathymetric derivatives, backscatter snippets, object size and shape.

2.2. Seafloor classification

If dissolved explosives are taken up into the food web depends on the local presence of flora and fauna (Beck et al., 2018, 2019; Strehse et al., 2017) and their distribution within the area which again is modulated by the sediment properties and the occurrences of hard grounds (Michaelis et al., 2019). Classifying the seafloor and describing and spatially discriminating habitats is thus an important task for investigating and monitoring munition dumpsites. To spatially define different seafloor classes the ArcMap 'ISO-Cluster and Maximum Likelihood Classification' tool was used. The ISO (iterative self-organizing) algorithm defines the likelihood of each grid cell belonging to a certain unimodal cluster. With each step it calculates the Euclidean distance of each cell value of the chosen input raster layer (slope, mean backscatter, TPI, general curvature and backscatter) to the mean value of a cluster. For each step, the cells are sorted to the closest mean value. Within the next calculation steps, the mean value are recalculated based on the associated cell values and the cells are newly fitted. In this way, the cells are refitted by steadily optimized mean values. The more cluster have been predefined (here we used 5 clusters as target number), the more refitting steps should be conducted. At the end of the process no more cell should switch an associated cluster. Based on these created likelihoods, the 'Maximum-Likelihood Classification' algorithm creates a raster of the cluster classes (Calvert et al., 2015). As input raster set a combination of seafloor backscatter snippets (backscatter mean) and morphological derivatives was chosen as shown in Table 3.

The bathymetry is not included, as the seafloor properties do not depending on the water depth. As ISO-clustering is unsupervised, no direct explanation of what the different clusters stand for is given. Based on annotations of underwater videos and photos, diver descriptions of the seafloor and sediment analysis, the clusters are associated with distinct seafloor properties leading towards a seafloor classification and habitat description.

2.3. Ground truth data

Visual observations: A substantial set of ground truth data were gained through underwater video footage. While the vessel was drifting, a camera frame equipped with an online camera and two GoPro cameras

Table 3

List of data layers that were used for the unsupervised seafloor clustering.

No.	Data layer type	Cell size
1	Backscatter Snippets Mean	0.25 m
2	Surface Area	0.25 m
3	Slope	0.25 m
4	TPI (irad = 0.25m; orad = 1m)	0.25 m
5	General Curvature	0.25 m

was towed alongside the vessel, less than 1 m above the bottom. The records were annotated using the software Ocean Floor Observation Protocol (OFOP; Huetten and Greinert, 2008). This software allows replaying the full videos linked to the logged navigation data. Parallel to the replay, the video is annotated by clicking predefined annotation classes. The resulting table contains position and adjacent annotations and can be e.g. plotted in a GIS program. Nine different seafloor properties were annotated including the seafloor coverage with vegetation or stones (Table 4).

Due to the shallow water depth, the position of the towed camera above the seafloor was derived from a ship based mobile GPS antenna, which was placed on top of the outrigger assuming no further offsets between the GPS antenna and the camera position above the seafloor.

Sediment Sampling: Sediment samples were taken by scientific divers of GEOMAR and Kiel University as well as Navy divers from WTD71 in Eckernförde based on the generated seabed classes (Table 5). At each station, divers took one sediment sample, a photo and made a description of the seafloor properties (estimated grain size distribution, vegetation, morphological features and presence of munition). Even though sampling stations were planned for each individual class, due to small scale seafloor heterogeneity and limited navigation precision underwater, often mixed classes were sampled or individual classes could not be reliably reconstructed. Class 3 for example, could not be sampled on its own at all (Table 5). For the ground truth 37 samples were accounted, for which a clear position and therefore the adjacent seafloor classes could be assigned to. Depending on sea conditions, accurate navigation with the surface vessel was very challenging. Deviations of 5 m of the planned sampling site from the actual sample location were expected. To minimize this error, sediment sampling locations were planned based on the classification map by selecting the largest possible connected area of the same class.

Quantitative grain size distribution data were derived inside the lab from sediment samples via a coulter counter laser particle analyser (Analysette-22 Nanotec, Fritsch GmbH). Results are expressed as particle percentage. As the measuring range is from 0.0001 mm to 1 mm, coarser samples needed to be wet sieved at 1 mm prior the analysis. Afterwards particle percentages were re-calculated to weight percentages including the sieved fraction(s).

3. Results and discussion

3.1. Bathymetry and MBES backscatter

In addition to MBES bathymetry, MBES backscatter snippets, which were generated at the same time, provide further information about different sedimentary properties and their spatial distribution. Kolberger Heide is rather shallow and its proximity to the coast leads to sediment input from shore and sediment redistribution due to waves and currents. The snippet backscatter image (Fig. 5) reveals a very heterogeneous seafloor (−51 to −13 dB, uncalibrated backscatter) with patches of generally higher values in shallow areas whose number and signal strength decrease with depth.

On **meso-scale** the bathymetry is characterized by a shallow

Table 4

Different seafloor properties were annotated in the study area, Kolberger Heide.

No	Description
1	Sandy seafloor without vegetation/stones
2	<5% vegetation and/or stones
3	5–50% vegetation and/or stones
4	50–100% vegetation and/or stones
5	Sediment ripples
6	Rock/boulder
7	Bivalve shells
8	Bioturbation
9	Munition

Table 5

Number of sediment samples for each class. If classes could not be sampled individually, mixed classes were derived (e.g. class 1–2).

Class	class 1	class 1-2	Class 2	Class 2-3	class 3-4	class 4
number of samples	1	6	4	4	11	11

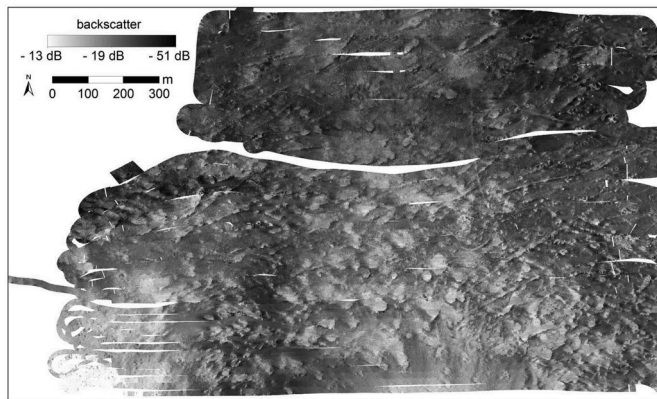


Fig. 5. MBES snippets backscatter showing the heterogenic seafloor composition of the Kolberger Heide area. High backscatter values (white) indicate rougher/harder seafloor compared to low values (black). The backscatter dB scale is not calibrated.

platform, which extends from the shore and deepens with less than 1° towards the north into a flat plain in 19 m water depth (Fig. 6; A).

The **macro-scale** level reveals patches with increased rugosity (height differences of 2–4 cm). Those areas produce a high backscatter response due to ripple structures and an increased amount of coarse material, such as gravel, stones and boulders (Fig. 8). Explosion craters with average diameters of 20 m and depths of 1.5 m are either spread as clusters or isolated craters across the entire study area. They were formed by blow-in-place detonations; such detonations partially acted as test cases for bubble curtain experiments. Bubble curtains significantly decrease the sound energy of detonations and thus particularly protect marine mammals (Würsig et al., 2000). Remnants of these bubble curtains in form of pipelines were left on the seafloor (Fig. 6; B and C) and can be reactivated if needed. Another interesting pattern is visible in Fig. 6; B: East of the craters a 4 m wide track structure extends in NW-SE direction.

Zooming into **micro-scale** level reveals that this track is composed of numerous single objects (ca. 1 m) placed in very regular distances of 30 m (Fig. 6; C). Smaller objects (<0.5 m) occur in between, which have not been identified yet. The regularity indicates a rather anthropogenic formation and is interpreted as on-route dumping. On micro-scale all kind of UXO and DMM objects can be observed in high numbers together with rocks and boulder patches of glacial origin. Besides this, a high number of suspicious objects can be found scattered all over the mapped area (Fig. 16). In some areas objects occur in higher density. One area is composed of at least 78 defused moored mines, piled up to a mound structure (Fig. 8) of 30 m length, 15 m width and 1.5 m height ('mine mound').

A second highly contaminated area is located around another cluster of detonation craters (Fig. 6; D, E). At this location around 90 munition bodies of different types including German and English ground mines, torpedo heads, water bombs and moored mines have been found ('craters'). Their state of corrosion is very variable, which is depending on factors that have been described in Silva and Chock (2016). Unfortunately it is not possible to determine, which the dominant corrosion process here is. Some of these objects were brought into the dumpsite

after they were found in ship traffic ways and were defused by the EOD. The third area of around 150 m² in size shows ca. 100 objects of 1 m by 0.6 m (Fig. 7 'bomb field'). First validation dives identified these objects as aerial bombs, which are most likely not defused.

As shown above, depending on their type, munitions can be more or less clearly identified without additional groundtruth (Table 6). The available MBES beam-opening angle of $0.5^\circ \times 1^\circ$ leads in 10 m water depth to a horizontal resolution of 0.09 m \times 0.18 m in the nadir and 0.35 m by 0.66 m at the outer beams (120° swath, assuming flat seafloor and that the footprint is not pulse-length dependent). With these settings in mind we found a minimum of 1,136 features that were manually identified as munition objects within the bathymetric data (Fig. 16).

Ground mines and torpedoes can be rather easily identified by their size and their elongated shape. Unfortunately smaller objects such as bombs and torpedo heads are less distinct and require additional visual validation by divers or underwater footage. Moored mines on the other hand occur as round objects with ca 1.2 m diameter and can be misinterpreted as large boulders. Fortunately, the joint analyses of the bathymetry, its derivatives and the backscatter snippets greatly enhance the detection and identification of munition. Slope, surface area and curvature highlight distinct features and objects like rocks and munition on the seafloor very clearly (Fig. 8). Compared to rocks, mines often appear more regular in size, shape and their derivative values (Fig. 8; A, I, B.I). Additionally, backscatter snippet data from moored mines show a significant signature with high and low values that nicely image the spherical shape of the mine shell. It scatters most of the signal leading to generally low response amplitudes; only the directly reflected wave from signal-facing surfaces creates a high backscatter response due to the hard metal shell (Fig. 8; B.II). Although well preserved mines show a characteristic backscatter pattern, the signal can be influenced by sediment coverage, the overgrowth by sessile flora and fauna and/or the corrosion state of the munition shell. Therefore, additional detection criteria were the surrounding sedimentary facies and the characteristics of arrangement. One example is the track of munition in Fig. 6; B: Even though objects do not show unique shapes, the regular distances to each other suggest on-route dumping of munition rather than naturally occurring rocks. The here identified types of mines are equivalent to those that Kunde et al. (2018) found north of Kolberger Heide and with the munition types compiled through the historic analysis presented in chapter 2.1. Nevertheless, only objects of detectable sizes as shown in Table 6 could be included. Historic analysis and diver records suggest even more objects and bare explosives in the area, which however are below the MBES detection limit.

3.2. Seafloor classification

As the whole area is spatially very heterogenic, we decided to use backscatter in combination with the bathymetric derivatives for an unsupervised classification. Only then a wide range of different seafloor environments can be represented (Calvert et al., 2015).

ISO clustering using the five input-parameters of Table 4 resulted in four spatial seafloor classes (class 1 to 4) and one class, which represents micro scale features (class 5).

Of the whole area 13% is covered by class 4, which represents macro scale patches of high backscatter, high curvature-, TPI- and surface area-values and predominantly occur in shallow areas of <10 m water depth (Fig. 13; class 4). These patches are generally surrounded by seafloor that has been assigned to class 3 (24%) and gradually change to class 2 (28%) and class 1 (17%), which occurs more to the north in deeper waters. The derivatives backscatter and slope show the main changes across the classes. Here, maximum values increase from class 1 towards class 4 (Fig. 9). The other derivatives only change about 1% (mean values). The range from minimum to maximum values increases from class 1 to class 4 for all parameters, except of the surface area. The data was normalized to the minimum and maximum values in class 5. Because the differences to the values in the other classes are so high,

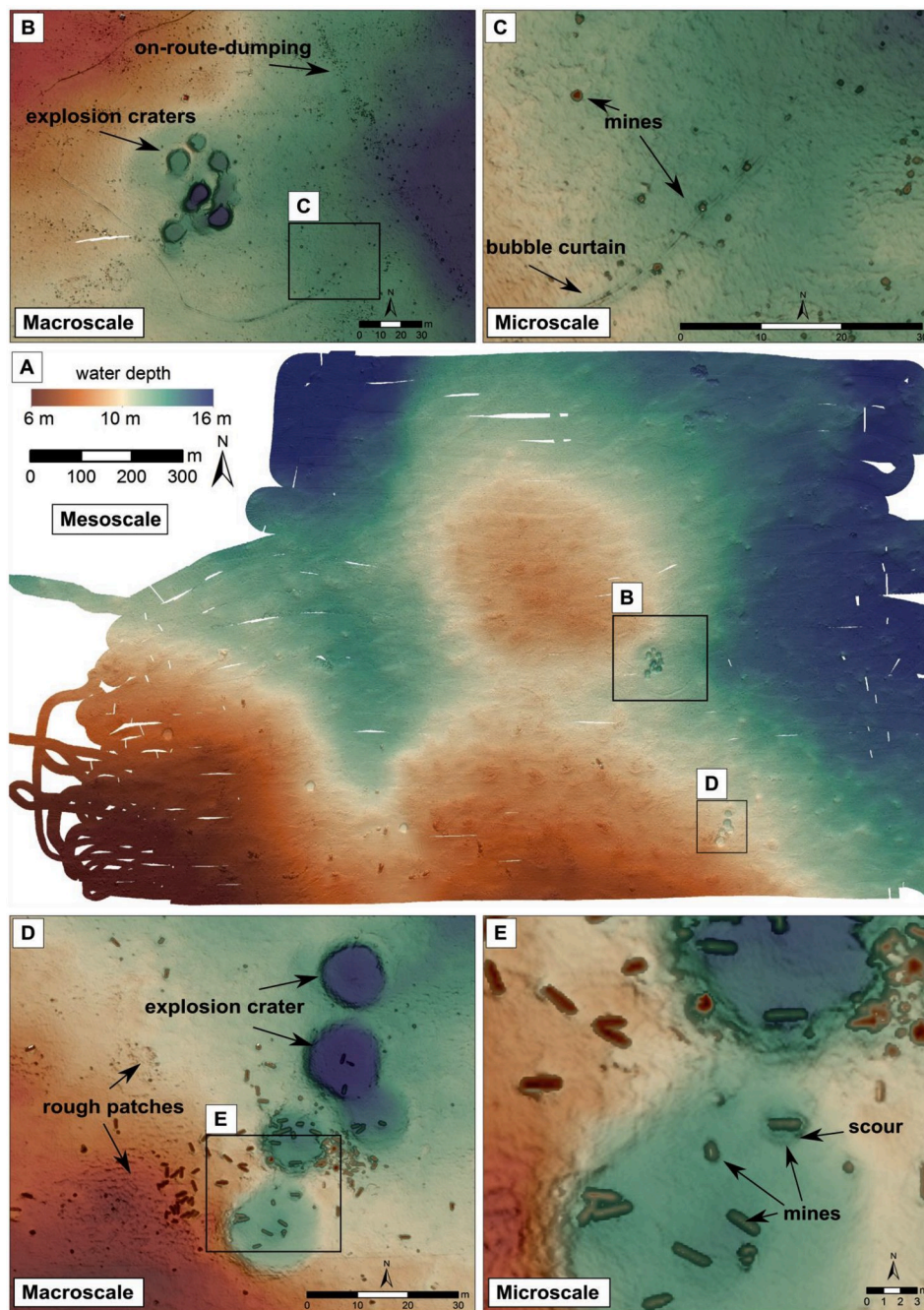


Fig. 6. The high resolution MBES map shows different scales of morphological features. A: Overview bathymetric map of the dumpsite Kolberger Heide with water depths from 6 to 16 m. B: Macroscale features like old explosion craters and an on-route-dumping track. C: Microscale features reveal single munition objects next to the remnants of a bubble curtain tubing system. D: Five explosion craters of around 25 m diameter. Patches of increased rugosity are visible. E: Close-up of groundmines in and around explosion craters.

changes seem less distinct in there.

Class 5 cannot be directly compared to the other classes, as it marks single micro scale features and not spatial areas. It is characterized by wide ranges of values for all input parameters (backscatter, slope, surface area, general curvature and TPI) indicating steep slopes and high reflective surfaces (>29 db backscatter).

3.3. Ground truthing

3.3.1. Visual observation

Ten underwater video transects were undertaken in the area with varying quality depending on the visibility in the water. The average visibilities ranged from 0.5 to 4 m. In areas where algae cover the seafloor, the substrate underneath could hardly be identified. Other features like sediment ripples, bioturbation, fauna, munition objects and

open explosives could be detected during towed camera surveys and were further investigated by divers. In general, the Kolberger Heide is characterized by sandy areas with patches or wider areas of algae. Highest abundance shows the red algae *Delesseria Sanguinea* (Appendix, Fig. 20). Algae are often accompanied by small sponges and fauna like star fish or mussels. Flat fish and other fish are common in areas with algae and hard substrate. From underwater video footage it was often not possible to clearly discriminate between rocks and munition, if the respective object is strongly overgrown. This was also true during direct diver inspection.

In some areas glacial till was exposed at the seafloor with only a thin cover of sand. These areas usually provide a good hard substrate for sessile flora and fauna (Kautsky and Kautsky, 2000). Stretches with sandy sediment either show current ripples and/or bioturbation with worm mounds on the surface. In some areas mussel shells of *Mya*

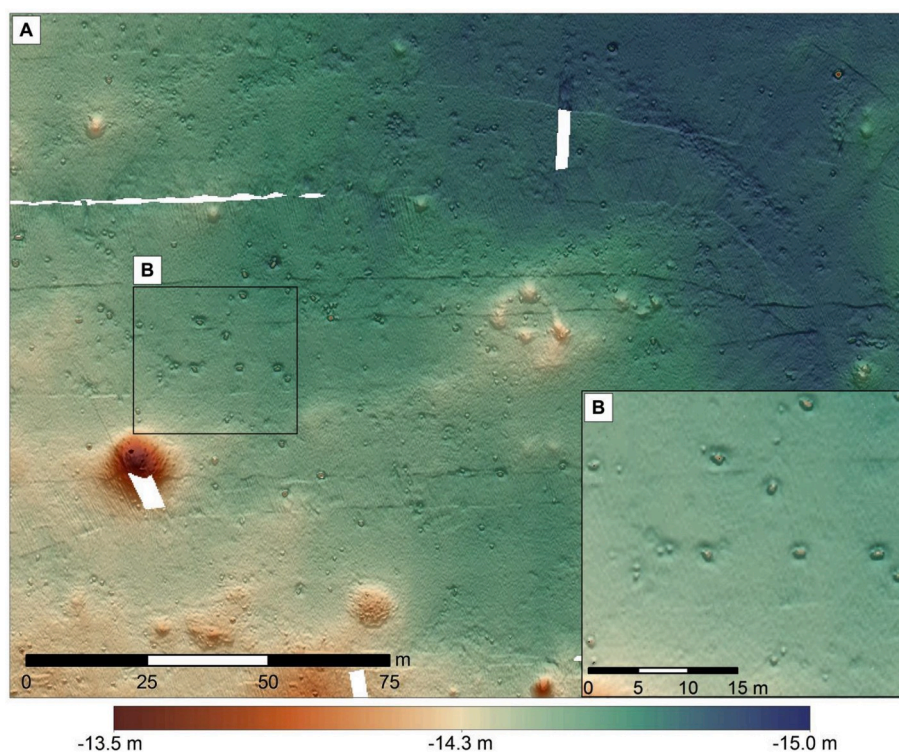


Fig. 7. A: Numerous objects of ca 1 m by 0.6 m size are spread on a field of 150 m². Some of the objects were identified by divers as aerial bombs. B: Most of the objects are affected by symmetric scours.

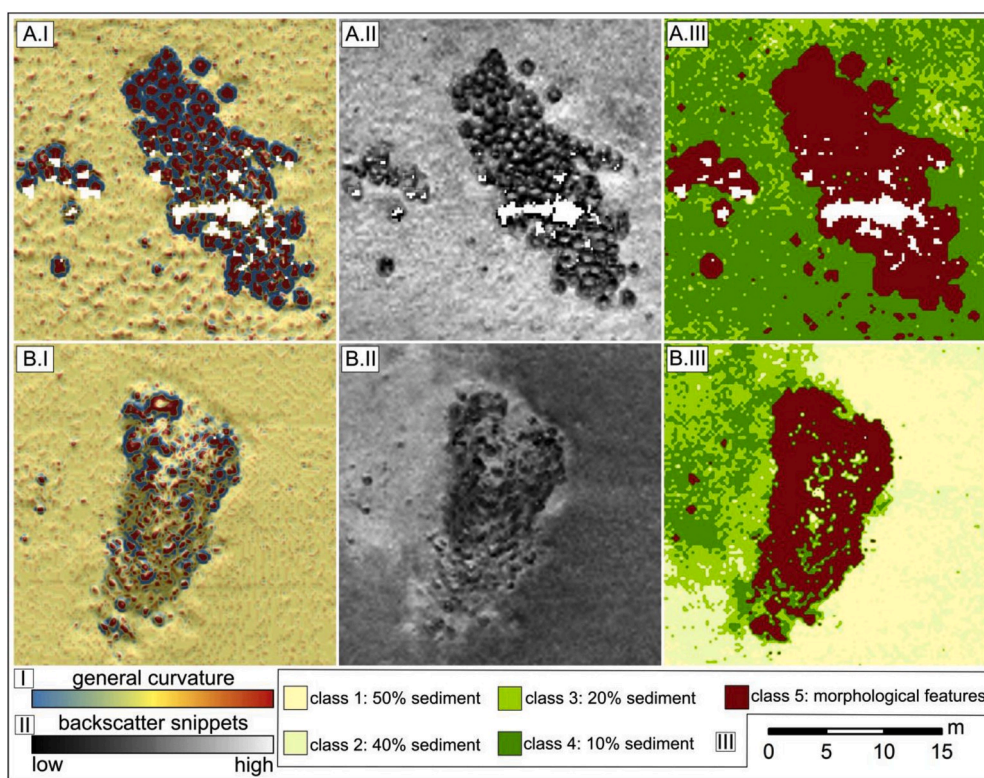


Fig. 8. Comparison of ca. 78 moored mines (A) versus a mount composed of rocks and boulders (B). The moored mines have a more regular shape (1.2 m diameter) and high general curvature values (I) and low backscatter (II). Nevertheless, both features are classified as the same class using the ISO maximum likelihood algorithm (III; red). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 6

Types of munition, which are expected inside the dumpsite Kolberger Heide, are given with their dimensions and probability of detection inside high-resolution multibeam datasets (dimensions based on Mine Identification manual 1945, US Navy).

Object type	diameter	length	detectable in MBES
moored mine	0.80–1.30 m	–	yes
ground mine	0.45–0.66 m	≤3.20 m	yes
aerial bombs	0.15–1.00 m	≤2.50 m	likely
grenades and propellant charge bags	0.02–0.38 m	≤1.50 m	unlikely
torpedoes	0.40–0.53 m	≤7.00 m	yes
torpedo heads (defused)	0.45–0.53 m	1.18–1.24 m	likely
depth charges	0.33–1.00 m	1.00 m	yes
hand grenades	0.05–0.10 m	0.08–0.15 m	no

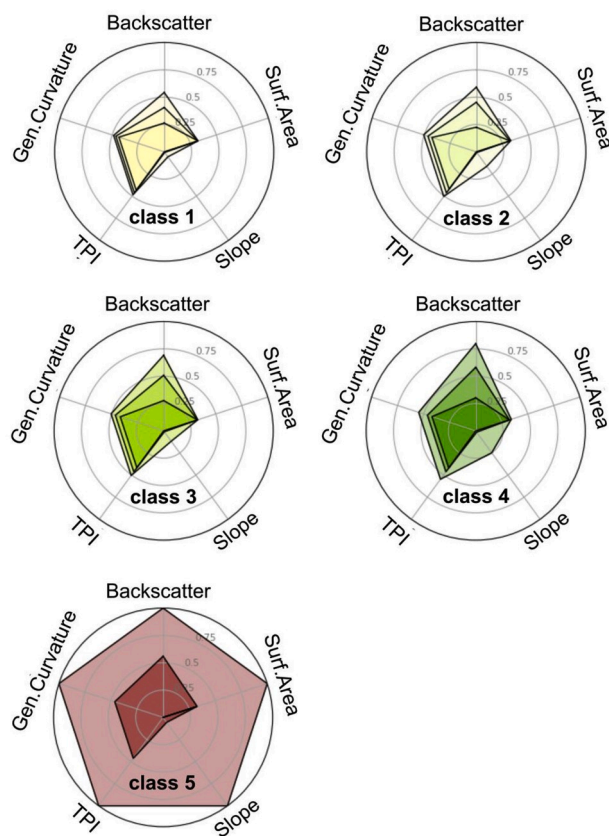


Fig. 9. Radar charts for each ISO cluster show the change of each input variable from one class to the other. The data were normalized from 0 to 1 and in each chart the maximum, average and minimum values are plotted. Main shifts are in the backscatter and the slope data. Maximum values of each variable occur within class 5, which clearly distinguishes from the other classes.

arenaria can be found.

Explosive material is clearly distinguishable from rocks by its angular shape and the fact that such blocks always show fresh surfaces which are not overgrown with a biofilm. An area of ca 6 m² has been identified to contain an increased number of open explosives (Fig. 10; C, D). Depending on the composition of the explosive it can vary in colour and weathering behaviour. Most blocks that were found are grey with metallic grains and a dark crust. Another type shows an orange matrix with yellowish pieces inside (see Beck et al., 2019). From both types, blocks of tens of cm size as well as smaller pieces of few cm occur in Kolberger Heide. Larger pieces are often partly covered with an unspecific biofilm, algae and rarely with mussels (*Mytilus edulis*; Fig. 10; C).

Photo observations by divers show that the corrosion state of moored mines is already advanced. Most outer housings show holes, are broken or almost gone whereby the internal housings containing the explosives are often still intact. During dumping of sea mines they were often shot at to flood their flotation body and make them sink. Shells of water-bombs and ground mines appear less affected by corrosion.

3.3.2. Sediment analysis

Regarding the fact that less samples could be assigned to class 1 and class 2, it is not possible to state a reliable trend in grain size from class 1 towards class 4. Most samples are composed of fine to medium sand with low amounts of silt (Fig. 11). Silt-dominated samples do occur in mixed class 2–3, 3–4 and in class 4. Class 3–4 and class 4 additionally contain a coarse sand fraction, which was not observed within the other seafloor classes. It seems that the sediment becomes less homogeneous towards class 4, but additional samples are needed to support this assumption. Diving was limited to fair weather conditions and available ship time and was therefore not possible directly after the MBES survey. Therefore sediment rearrangement and the influence of different seasons can also bias the sediment-to-class correlation. Additionally, the sample can be biased, as the diver might not collect the sediment objectively/representatively; larger rocks might be avoided if it does not fit into the sampling container or sediment was not collected if it was overgrown by epiphytes. On the other hand, the photos and seafloor descriptions of each station depict a wider picture of the surrounding, compared to a grab sample.

However, the grain size analysis emphasizes that the surface sediments throughout the area are similar and fine to medium sand is the main fraction. Mixed sediments (silt, medium sand and coarse sand), are typical for glacial till. The results coincide with the underwater video observations.

3.3.3. Habitat classification

Combining the results from the towed underwater camera observations and sediment samples with the ISO maximum likelihood classification, four habitats were identified based on the amount (in %) of uncovered seafloor (free of vegetation). One additional class describes mines, boulders, artificial features and explosion craters but no spatial vegetation coverage. The number of video annotations regarding the sediment coverage was assigned to each class of the ISO cluster map to derive an integrated description for each class (Fig. 12). In each class all annotated levels of algae coverage were present and a clear decrease of uncovered sediment is visible from class 1 to class 4 (Fig. 12).

The increase of algae coverage positively correlates with increased seafloor roughness and increased backscatter amplitudes as shown in the radar charts in Fig. 9. As algae need hardgrounds to grow on, their occurrence might be an indicator for remnants of outcropping glacial till deposits (Fig. 13). The very similar sediments of fine to medium sand across the entire area suggest that a more or less thin sandy sediment layer overlays the glacial till. This till also contains coarse material which supplies the larger boulder and pebble size rocks on the seafloor surface. The occurrence of rock size components could not be represented by the sediment grain size analysis due to sampling bias. The class description is based on the HELCOM underwater habitat and biotope classification for the Baltic Sea (Avellan et al., 2013) (Table 7).

The combination of hard substrate as boulders but also munition shells, as well as the fact that the dumpsite is restricted to fishery, makes the Kolberger Heide a habitat for a wide and rich variety of marine organisms. The munitions seem to be incorporated into the local ecosystem suggesting an enhanced exposure of marine biota to toxic munition related compounds. This has also been observed by Edwards et al. (2016) via a time-lapse study on Hawaii, which displays the interaction between sessile and mobile fauna with DMM. Strehse et al. (2017) showed that invertebrates (*Mytilus edulis*) collected next to open explosives (Schiesswolle 39) showed high TNT concentrations inside their tissue and prove that explosives do enter the food web.

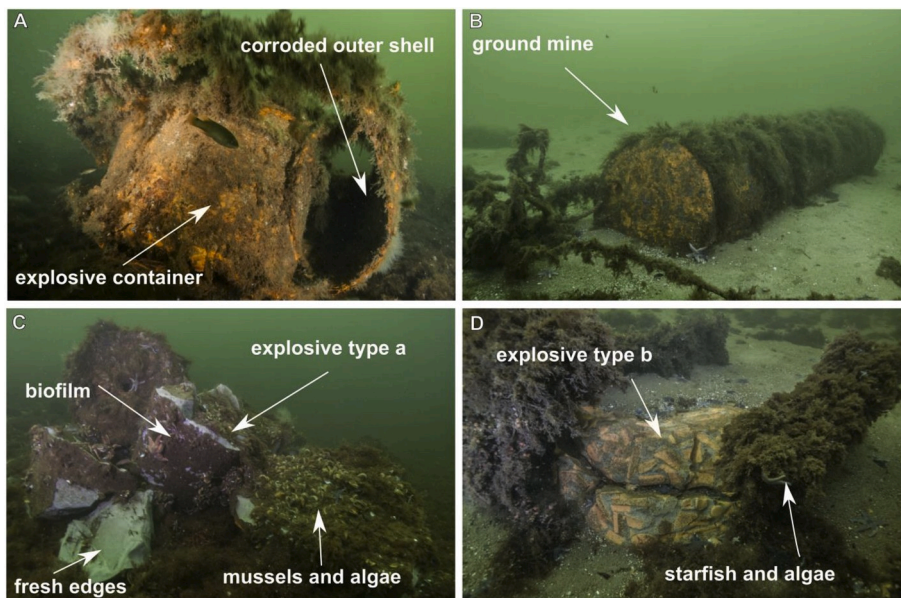


Fig. 10. Underwater photos taken by Jana Ulrich. A: A German moored mine, where the outer shell is almost fully corroded. B: A British ground mine on sandy seafloor. C: Inside the area blocks of explosive are exposed. They are covered with a biofilm and mussels, but also show uncovered fresh explosive faces. D: Another type of explosive of mixed composition and orange/grey colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.4. Munition migration and its link to seafloor properties

Within sandy areas where the seafloor is characterized by 50% uncovered sediment, bioturbation and current ripples often occur. Ripples clearly indicate vertical and horizontal sediment transport which, based on the observation of Beunaiche (2017), changes over time causing ripples to disappear e.g. after storm events. Around the site of the old blown-in-place craters about 70 munition objects rest on the sediment, easy to detect within the MBES data. Scours have formed around some of the mines (Fig. 6, E). Two datasets of this area, were acquired within 4 months and have been compared for the position and orientation of the detectable ordnances (Fig. 14, A, C, D). Between both surveys a storm occurred in March 2019 with wind speeds of up to 18.70 m/s. For comparing both data sets the older data set is coloured in red and the younger one was plotted in transparent blue on top in Fig. 14. On a first glance, most objects did not migrate. But one object shows a migration of 2.5 m and additional objects show changes in orientation and displacements of 1–2 m. For more long-term comparison data from an R2Sonic system, acquired in 2015 (WTD-71) is compared with the youngest data set from June 2018. The position accuracy was less in 2015 and the data contains varying shifts of up to 1.5 m in longitude and 1 m in latitude-direction. Because the shift was not constant and could not be corrected completely, changes in object position, e.g. displayed in Fig. 14; E, are not fully reliable. Obvious changes still become visible in comparing Fig. 14; D and E: In February 2018, one mine was temporarily not detectable, maybe due to sediment coverage.

The results of multibeam monitoring show rather stable conditions for the position and burial of munition bodies. This is supported by literature results. Critical incident velocities from 0.41 m/s – 0.78 m/s were determined by Menzel et al. (2018) to be required for mobilizing objects such as a British General-Purpose Bomb, German Mine Type GU and a model cylinder (with initial burial depths ranging from 5 to 50%). The required critical incident velocity increases with the percentage of burial and is lower for the model cylinder compared to the British General Purpose Bomb (0.65 vs 0.78 m/s by 50% burial). In contrast: our modelled current velocities in Kolberger Heide hardly exceed current velocities of 0.1 m/s, which are too low to actively move mines. Most of the year the main current direction in Kolberger Heide is from NW to SE (Fig. 4), which is in accordance with the observed ripple aspect direction. Maximum bottom current velocities occur most frequently during winter time. A strong storm in March 2018 with wind velocities of 18.70 m/s generated wave heights between 1.60 and 2.80 m and bottom

water currents that increased to 0.35 m/s (Fig. 15) which are still below the needed values given by Menzel et al. (2018). Therefore this storm cannot explain the mine migration of 2.5 m during the same time period.

Another migration mechanism was observed during experiments with Burial Recording Mines (BRMs) in the North Sea. Bayes (2012) and Papili et al. (2014) show that storm events can lead to scour formation around mines and instead of being actively moved they rather roll into the scour depression. When the storm decays, they can become partly or fully buried by settling sediment (Inman and Jenkins, 2002; Papili et al., 2014; Rennie et al., 2017). The horizontal migration in this case is very limited; high energies are needed to remobilize an object once it is settled inside a scour. The potential of scour formation and subsequent burial is depending on the erosion potential of the seafloor (Mohr et al., 2016).

Scours formed by constant currents are caused by erosion on the luv side of an object (Trembanis et al., 2007; Callaway et al., 2009). The scours within the research area are almost symmetric around the objects (Fig. 7), which rather indicates a wave-induced formation (Inman and Jenkins, 2002). Scour depths reach 20 cm. Field studies revealed that waves produce high bottom orbital currents that can lead to rapid scour formation and burial of objects (Trembanis et al., 2007; Inman and Jenkins, 2002). However, the modulation and prediction of scour formation around objects is rather difficult, as it depends on a number of physical parameters, such as the type of mine (shape, weight, size), initial burial depth, boundary shear stress, water depth, wave height and – period, seabed topography and sediment grain size (Rennie et al., 2007). In Kolberger Heide, scours can mainly be observed within areas of habitat classes 1 and 2 with (50% or 40% of uncovered sediment, but less in class 4, which is a mix of sediment with rocks and only 10% of uncovered seafloor surface. Using the equations described in Papili et al. (2014), the critical wave height (H_{cr}), which is necessary to mobilize sediment grains on the seafloor in a certain water depth, was calculated. This was done for three different grain sizes: medium sand, fine sand and silt at a water depth of 10 m. The respective time period was chosen from February to April 2018 to cover the storm in March 2018.

The comparison of H_{cr} to the significant wave height (H_{sig}) (provided by the Federal Bureau for Maritime Navigation and Hydrography (BSH); data in vicinity to Kolberger Heide) allows to detect events when $H_{sig} > H_{cr}$, which might lead to sediment mobilization (Fig. 16). The critical wave height is strongly coupled to the wave period. During storm events the wave period increases, which reduces the critical wave height that is necessary to mobilize sediments. The finer the sediment; the

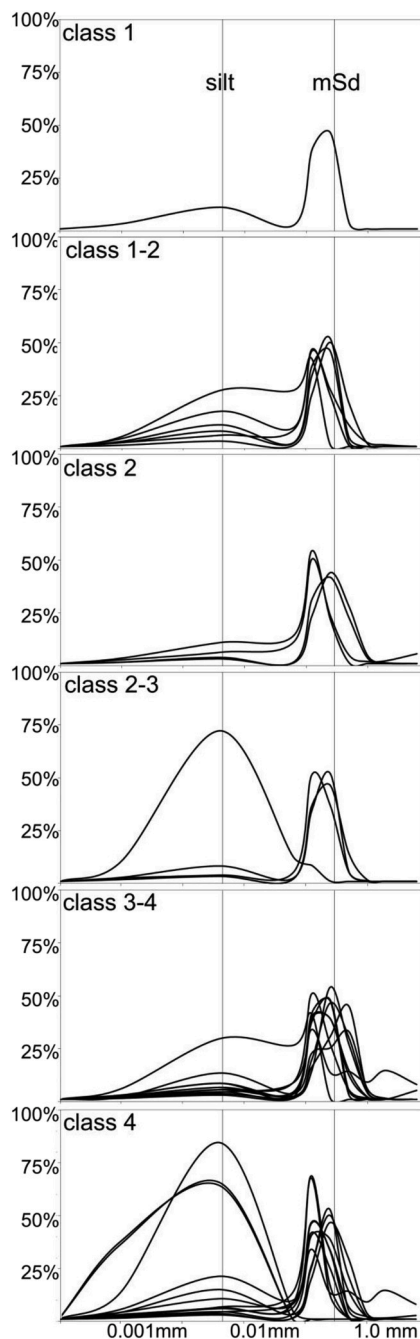


Fig. 11. Grain size distribution curves for ISO classes 1–4 and transitions and mixed classes. Class 3 could not be sampled on its own. The vertical lines mark the sediment classes silt and medium sand (after Wentworth (2008)).

easier it can get mobilized (only applies for non-cohesive sediments). Within the time period from February to April 2018, three strong wind events occurred when the significant wave height exceeded the critical wave height for fine and medium sand, whereby the storm in March was the most distinct event. Even though the calculations neglect factors like mixed sediments, the seabed topography, seafloor coverage with vegetation, local influence due to objects and the availability of free sediment; it gives an indication of the seafloor stability during the given time. Similar calculations can be applied to get spatial information about potential sediment remobilisation if sediment properties are known. For Kolberger Heide areas of habitat classes 1 and 2 are more vulnerable to sediment mobilization than classes, which are stabilized by vegetation. Within class 1 and 2 scour formation and subsequent object burial must

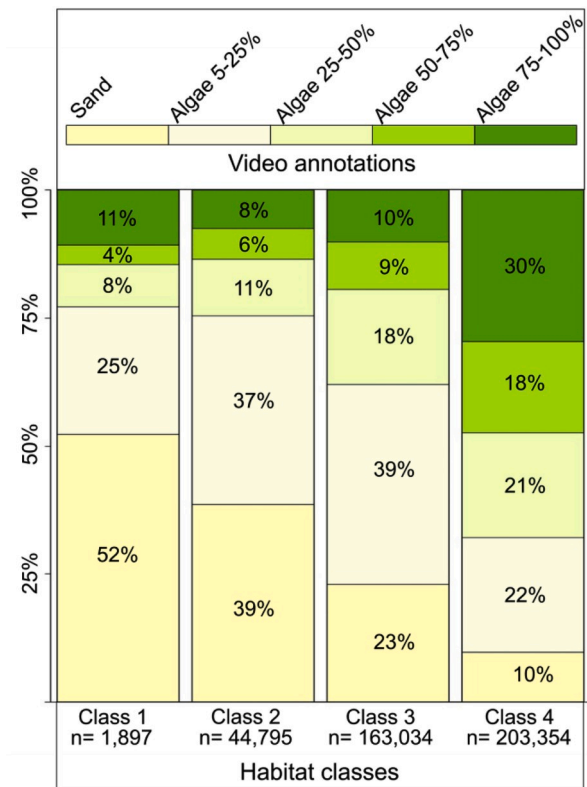


Fig. 12. Comparing the underwater video annotations to the ISO classes 1–4 shows a clear decrease in uncovered sediment and an increase of the coverage by algae. As class 5 represents features and no environments, it has been neglected here. The Y-axis indicates the proportion in % of each video annotation for each class and 'n' gives the number of annotations per class.

be expected. It is not completely clear if the storm in March 2018 could have caused movement and rearrangement of mines, as displayed in Fig. 14. No deep scours can be observed around the craters, which could be due to the limited sediment thickness on top of an abrasion platform of glacial till. When the object is not centred within a scour, its migration potential might be increased. The fact that not all munition objects were rearranged highlights the complexity and spatial heterogeneity of this topic.

3.5. Munition monitoring set-up

The remediation of marine DMM dumpsites is very costly and thus only specific areas will be targeted first (Schultz and Hodgson, 2011). Defining such specific areas is one aim of ongoing initiatives for a 'Decision Aid Tool' as envisioned in the DAIMON and DAIMON II projects. Important information such as presence, distribution, type and state of munitions on the seafloor are often not available and need to be established through prior baseline studies bearing in mind that some processes can only be assessed through longer term monitoring. The United States Environmental Protection Agency has released a guide for systematic planning, when data are used for contamination assessment (USEPA, 2006). According to this guide, a conceptual site model based on a baseline study is essential to identify the type of data, which are required to address certain relevant questions. The here presented work represents parts of such a baseline study for the Kolberger Heide dumpsite. Additional work regarding the geochemistry and toxicological characteristics is presented by Strehse et al. (2017), Appel et al. (2018) and Beck et al. (2018, 2019). As part of the UDEM project a practical guide for 'Environmental Monitoring of Conventional Munitions in the Seas' has been compiled based on the here presented studies (Greinert, 2019). Table 8 shows the recommended monitoring areas and

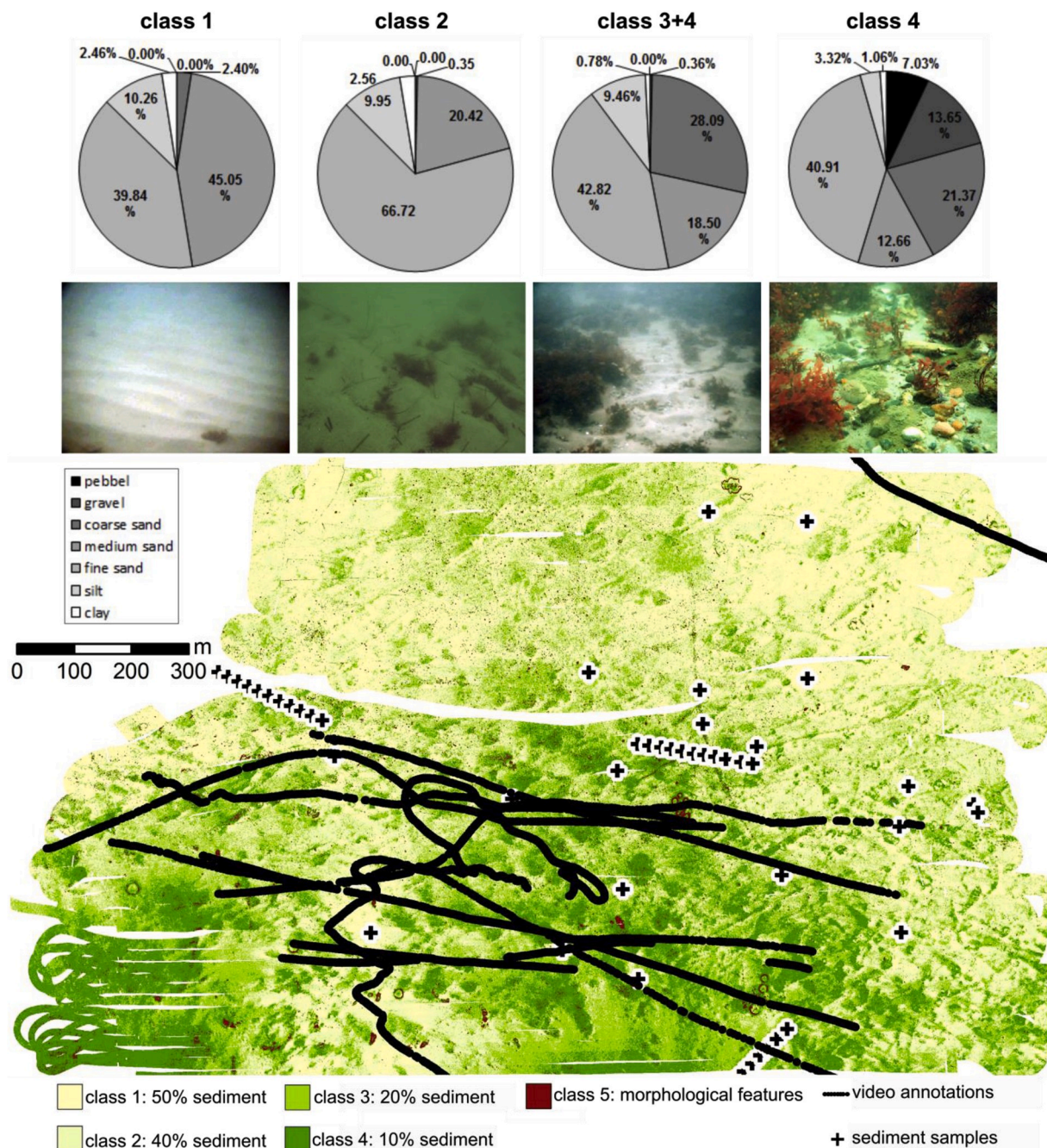


Fig. 13. Map with five derived seafloor classes, sediment sampling locations and underwater video tracks. The video annotations and the sediment grain size analysis were used to define a habitat to each class. In this figure, one exemplary sediment sample is given for each class. Class 3 (5–50% vegetation) was not sampled on its own.

recommended intervals for Kolberger Heide as an example for other munition dump grounds. Intervals and specific monitoring foci need to be adapted to the local conditions and findings and might be subject to changes during the time of long-term monitoring (USEPA, 2006).

High-resolution seafloor mapping proves to be an efficient tool for monitoring shallow water munition sites. The resulting maps allow the identification of areas with high contamination potential, areas in which changes through re-deposition, corrosion and burial are likely and areas in which additional survey methods are required (Table 8). The results from Kolberger Heide show that DMM is spread over the entire studied area (Fig. 17); as mapping is a time and cost extensive task, sub areas need to be identified for repeated mapping. Corroded mines and open explosives are present in Kolberger Heide, but within the frame of the

three years of observation no progressive corrosion rates were observed. The actual environmental contamination by dissolved explosive compounds could be measured and monitored through geochemical and toxicological methods including analyses of direct water samples (Gledhill et al., 2019; Beck et al., 2018, 2019), sediment, mussels from biomonitoring (Strehse et al., 2017; Appel et al., 2018) or through passive samplers. Optic approaches helped to identify those areas, which are best suited for repeated sampling with a recommended repeating interval of optic surveys of at least every five years. Since extensive migration of DMM does not seem to happen in Kolberger Heide, but burial and scour formation have been observed, we suggest high-resolution hydroacoustic monitoring every five years. Close to sensitive areas such as marine traffic routes, construction sites or

Table 7

Habitat classes derived from the seafloor classification in combination with the ground truth data (video annotations, diver descriptions and photos) and based on the HELCOM EUNIS seafloor classification.

ISO class	Habitat class	Habitat description
1	50% sediment	Baltic photic sand characterized by 50% uncovered sediment, bioturbation can occur
2	40% sediment	Baltic photic sand characterized by 40% uncovered sediment, bioturbation can occur
3	20% sediment	Baltic photic sand characterized by 20% uncovered sediment, few stones covered with perennial foliose red algae
4	10% sediment	Baltic photic mixed substrate characterized by 10% uncovered sediment, rocks and boulders dominated by perennial foliose red algae
5	Morphological features	Single boulders, artificial features (mines, bubble curtain), craters

beaches, shorter or event-based intervals might be needed. Since the here presented methods are limited to proud DMM, further surveys with ground penetrating methods, such as sub bottom profiler and magnetics/electromagnetics are required in defined areas (Table 8).

Based on the acquired data, three areas have been identified, which meet the requirements presented in Table 8 and thus should be the focus of future monitoring (Fig. 17). Area A (the ‘mine mound’) appears stable in terms of migration, but should be monitored in terms of toxic releases caused by ongoing corrosion and the high amount of explosives and the abundance of biota. In area B (old explosion craters) minor displacement of mines were detected. Additionally this site already acts as storage place for defused munition, placed by the EOD. High resolution mapping should be repeated here every five years to keep track of changes. As the

visual groundtruth revealed open blocks of explosives, a geochemical and biomonitoring of explosive compounds is needed. For area C (field of aerial bombs) it is advised to use additional sensors like magnetometer and/or subbottom profiler to identify potential buried objects.

Schultz et al. (2011) also describe the need of combined techniques for marine munitions site characterizations, as well as that a monitoring strategy should be economic and easily repeatable. Only if monitoring is done repeatedly and comparable, trends can be reliably observed and correctly interpreted. Multibeam mapping might not be able to detect buried munition, but it can reveal areas where migration or burial are likely and thus should be surveyed more often with ground penetrating techniques in support.

4. Conclusion

The example of Kolberger Heide shows that high-resolution multi-beam surveying is a well applicable state-of-the-art method for monitoring shallow water munition dumpsites. The military-historic reconstruction of a dumpsite influences the choice of survey methods as additional sidescan, subbottom or magnetic data acquisition, the respective survey planning and the final data interpretation. The high precision MBES data do allow for object detection and detailed migration reconstructions over time. Nevertheless, it is limited to physical parameters such as water depth and object size and can only be used for proud munition on the seafloor. In Kolberger Heide a total of 1,136 mines were identified in the bathymetric data within an area of 6.63 km². This is just a minimum number, which includes only distinct objects that were clearly identifiable due to their size, shape and setting. Predominant types are moored mines, ground mines, depth charges and torpedoes, which is consistent with the historic presumptions. A direct comparison to the number of 6,295 DMM as analysed from historic

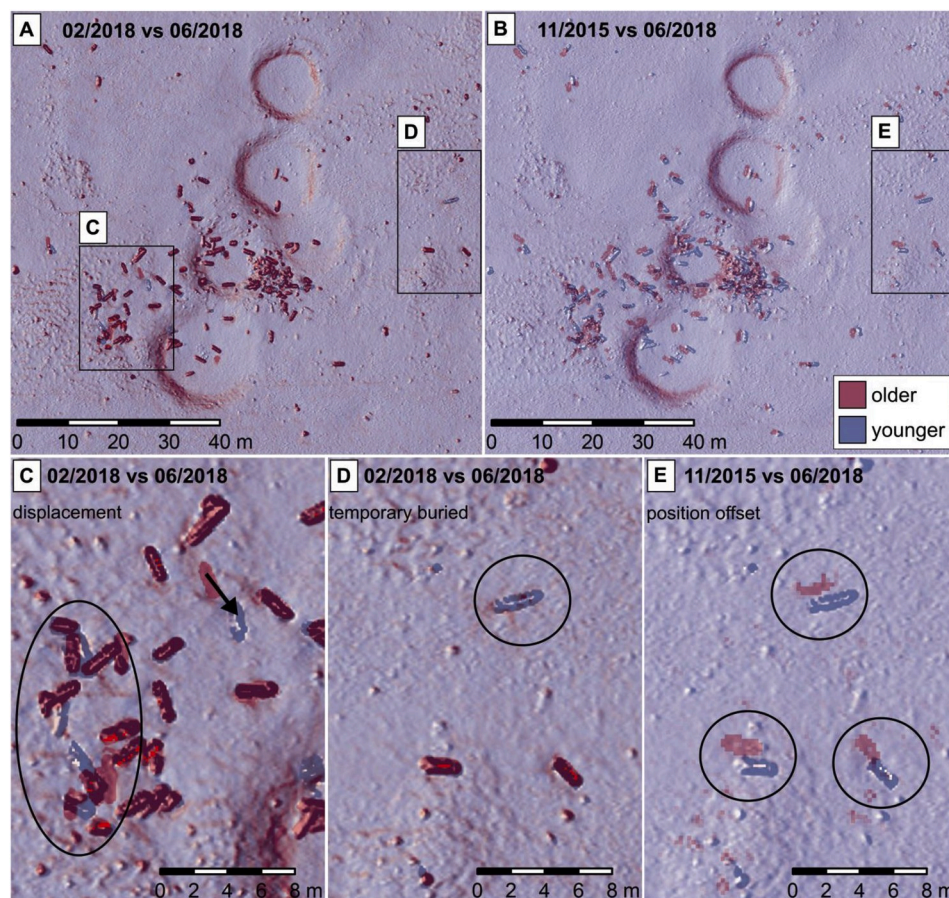


Fig. 14. Two different datasets of munition locations are compared over time (A, C & D: changes within 5 months; B & C: changes within 18 months). The younger dataset is displayed in blue, transparently overlaying the older dataset in red. A: RESON 50-P data from February 2018 is compared to RESON 50-P data from June 2018. B: R-2-Sonic data from November 2015 is compared to RESON 50-P data from June 2018. Offsets between data sets due to navigation uncertainties. C: Most of the mines stayed in place. Single objects moved or changed their orientation. D: Two mines did not move; one mine was not detectable during the February 2018 cruise. E: Offsets between data sets due to navigation uncertainties. The mine, which was not detectable in February 2018, was present in 2015. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

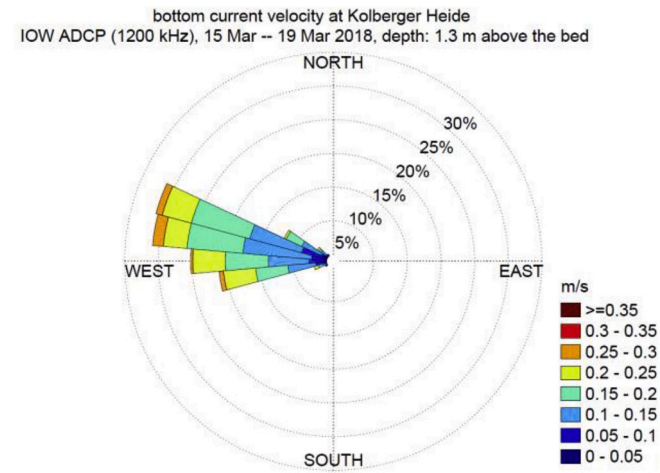


Fig. 15. Rose diagram of measured bottom current velocity during a storm event in March 2018.

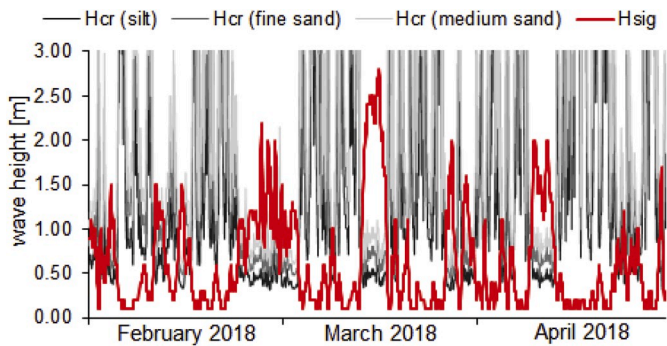


Fig. 16. Comparison of measured significant wave heights (H_{sig}) in red to calculated critical wave heights (H_{cr}) for three sediment grain sizes: silt (black), fine sand (grey) and medium sand (light grey). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

records is not possible, because no detailed information about exact dumping locations exists. Dumping also took place outside of the here studied area, as findings of Kunde et al. (2018) north of the official restricted area show.

We successfully used the ISO maximum likelihood classification method for an unsupervised seafloor classification based on bathymetric data, its derivatives and backscatter information. Linking the derived classes with groundtruth data from sediment samples and underwater videos resulted in five seafloor classes which are rather heterogeneously distributed. The simple applicability of the unsupervised ISO clustering algorithm makes it one of the first choice algorithms to test. Results show that wide areas are populated with typical local flora and fauna but in very different percentages of seafloor cover. This means that migration and burial mechanisms can be very different and that the interaction of flora and fauna (passively or actively) varies significantly across the studied area.

Repeated high-resolution mapping of one specific mine site revealed displacements after one specific storm event; another mine was temporary covered with sediment and not detectable in February 2018. This highlights that despite the theoretical incident velocities for munition migration (Menzel et al., 2018) being significantly higher than the recorded in-situ ADCP measurements show that migration and burial of munition still can take place. Mobile sediment indicated by scours and ripples is predominantly observed in areas with fine sand and 50% uncovered sediment. In such areas fewer mines were found on the seafloor.

Table 8

List of topics, which are relevant in terms of monitoring set-up and sub-area definition. For each parameter, corresponding sites within the dump site Kolberger Heide and the recommended monitoring intervals and methods are given.

Topic	corresponding sub-area	recommended monitoring interval and methods
1.Release of toxic compounds and subsequent environmental contamination	1.Mine mound (A): high abundance of corroded mines and high abundance of local flora and fauna 2.Old explosion craters (B): high abundance of mines + open blocks of explosives and high abundance of local flora and fauna	Every 5 years Optic surveys (AUV, divers) to document the state of corrosion Additional biomonitoring (e.g., blue mussels and fish) and monitoring via water and sediment sampling in shorter intervals recommended
2.Relocation of DMM into sensitive regions (marine traffic routes, nature reserves, beaches, construction sites, etc.)	1.Old explosion craters (B): only minor migration next to crater walls observed, but new objects are placed 2.Field of aerial bombs (C): fine sediment, scours already observed	Every 5 years Documentation of changes via high-resolution mapping Shorter intervals if migration towards marine traffic routes, beaches or fishing areas can be observed
3.Unsuitable/incomplete mapping methods for complete DMM indentification	1.Field of aerial bombs (C): fine sediment, scours already present	Additional mapping with ground penetrating sensor methods, such as Subbottom profiler and magnetics to evaluate abundance of buried objects

This might indicate that increased burial takes place in such areas but it also shows that even in rather stable environments careful monitoring with respect to munition migration and burial should take place.

Towards a long term monitoring strategy of a dumpsite we suggest a two-step-approach, consisting of a complete area survey during which sub-areas are being defined for subsequent repeated monitoring. Monitoring periods need to be adapted to the variability of the environment impacting the migration of munition and its corrosion status.

For a complete initial survey in Kolberger Heide additional ground-penetrating methods are required in addition to the above described MBES approach. As migration does not happen extensively, monitoring intervals of five years are recommended. The habitat mapping enabled to reveal different seafloor types with different potential for scour induced displacement and burial. In final conclusion it can be stated that munition objects and explosives became part of the subsea environment, causing its contamination with toxic substances. Therefore the state of corrosion as well as the extent of proud explosives on the sediment surface needs very close and quantitative monitoring to evaluated environmental risk for today and the future. Monitoring results should be fed into munition data management systems such as the Decision Support Tool developed by the Interreg project DAIMON (www.daimonproject.com) and the munition cadaster AmuCAD developed by EGEOS GmbH (www.amucad.org). This enables analyzing long-term trends and makes risk assessment possible. It is still a major task to identify the detailed amount and chemical composition of the munition and explosives within this area. Nevertheless, this information is essential for risk assessment and renovation plans (e.g., RoBEMM project). A multi-sensor-approach combining MBES, magnetometer, sub-bottom profiler and optical surveys in combination with artificial intelligence algorithms for munition detection, change detection and habitat classification should become standard to assure the objective interpretation of the data. There is no possibility to recover all munition objects from the marine environment and thus dedicated actions can only take place through a well-planned and informative monitoring on chosen sub-areas. The fact that Kolberger Heide is close to shore, water depths are low and entering by boat is prohibited but not controlled; this

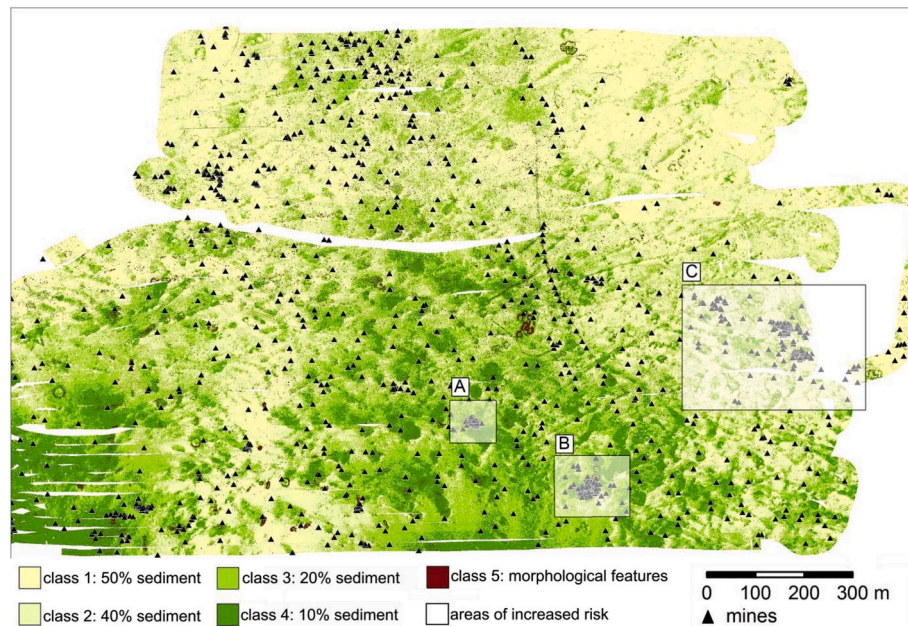


Fig. 17. Seafloor classification map with identified mines (stars). Based on the seafloor class and munition distribution three areas that require monitoring have been suggested (transparent boxes). A: Mine mound composed of moored mines; B: Old explosion crater site with ground mines; C: Field of aerial bombs in fine sediment.

adds the risk of human manipulation of this particular area. This might happen through illegal fishing, scuba divers or willing manipulation and recovery of explosives or munition objects. With ongoing publicity and rising public awareness of DMM, reinforced controls of respective sea regions are strongly recommended.

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Appendix

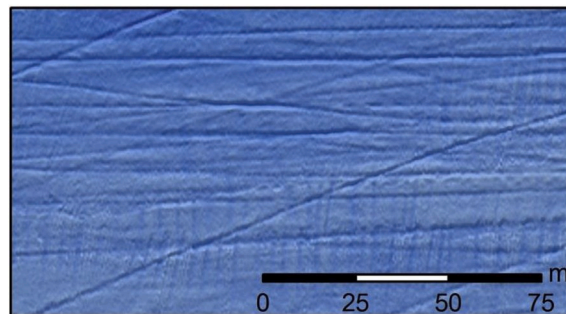


Fig. 18. North of the dumpsite in 19 m water depth, fishing marks from otter board trawling criss-cross the area and leave distinct furrows on the seafloor.

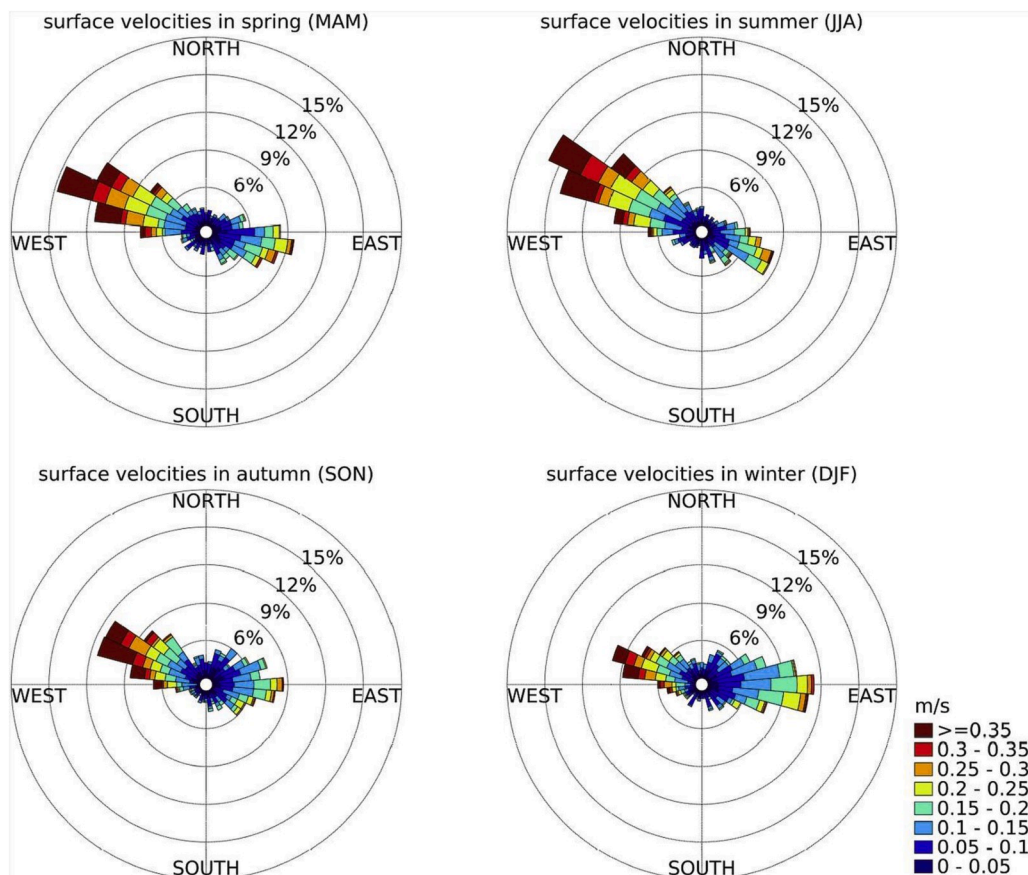


Fig. 19. Rose diagrams of modelled surface current velocities for four different seasons (spring, summer, autumn, winter). The velocity roses show the current directions grouped into 36 angle bins, with each bin thus representing a 10° span of the compass. From the middle of the circle the angle bins point into the direction in which the current is flowing and their length represents the relative occurrence of current directions within that angle bin.



Fig. 20. Red algae dominate the seafloor in the research area. They grow on hard substrate within the photic zone.

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